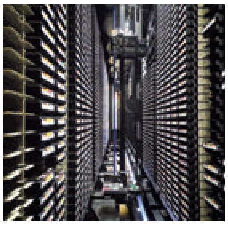
PARTICLE PHYSICS 2021.

Highlights and Annual Report

Deutsches Elektronen-Synchrotron DESY
A Research Centre of the Helmholtz Association



Cover
New tape robot in the computing centre at DESY in Hamburg

PARTICLE PHYSICS 2021.

Highlights and Annual Report

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The year 2021 at DESY

Chairman's foreword

Dear Colleagues and Friends of DESY,

German Nobel Laureates in physics and chemistry in 2020 and 2021 and the rapid development of a COVID-19 vaccine through the outstanding research and development work in the BioNTech company: These are spectacular scientific breakthroughs that impressively show the strong German role in worldwide fundamental and applied research.

To open up completely new possibilities of knowledge generation, DESY has a highly ambitious future plan at its two sites to shape the research campus of the 21st century. Here, applied research that leverages the potential of cutting-edge research infrastructures and rapid transfer to industry and society will be promoted and shaped in a smart "ecosystem".

To implement this plan in a highly competitive environment, we need to get important construction projects under way quickly in the current funding period so as not to fall behind internationally. This applies to the various construction projects in the areas of research, transfer and knowledge communication on the DESY sites in Hamburg and Zeuthen, but especially to the PETRA IV project, the world-leading lighthouse in research with synchrotron radiation. With the newly developed revolutionary storage ring technology, the hybrid six-bend achromat (H6BA) lattice, we are pushing the performance of German and European light sources ahead of those in the USA and China.

The lessons learned from the coronavirus pandemic and the acute climate crisis are forcing us to leave our comfort zones. For us at DESY, this means that we are questioning the daily life we have become used to. How will we work and conduct research at DESY in the future? How and how much will we travel in the future? How will we organise a sustainable research campus in the future? How do we coordinate climate-friendly operation for users at our large-scale research facilities without any compromises in quality? Will it then still be possible to be appealing to new user

Figure 1

DESY tour during the Karl Heinz Beckurts Prize ceremony in October 2021 (from left): Oliver Seeck, Wim Leemans, Roland Busch (Siemens), Helmut Dosch, Ingmar Hoerr (formerly CureVac), Vasilis Ntziachristos (Helmholtz Zentrum München and TU München), Venetia Ntziachristos, Christian Stegmann, Arik Willner

Figure 2
The newly opened Start-up Labs Bahrenfeld building close to the PETRA III experimental hall "Max von Laue"

groups from academia and industry? If we find the right answers and smart solutions, I am convinced that DESY will remain a future-oriented research centre, perhaps even more diverse and even more climate- and family-friendly, and continue to attract the best talents from all over the world.

In October 2021, we were privileged to host the award ceremony for this year's Karl Heinz Beckurts Prize at DESY. The Karl Heinz Beckurts foundation, which confers the prize, was established by the Helmholtz Association together with Siemens AG. Alongside the prize winner Vasilis Ntziachristos (Helmholtz Zentrum München and TU München), Ingmar Hoerr (formerly CureVac), Uğur Şahin and Özlem Türeci (BioNTech) were also honoured with a special prize. The guests included Roland Busch, CEO of Siemens, who was very impressed by the tour of the DESY site. Personally, I was touched by the first names of the award winners: Vasilis, Ingmar, Uğur, Özlem. There is no shorter or better way to show where our future lies – DESY has lived this diversity since its foundation.

This year, DESY signed the Diversity Charter ("Charta der Vielfalt"), thus becoming part of Germany's largest diversity network. DESY is actively committed to a diverse and prejudice-free working environment and to the appreciation of all employees regardless of their gender and gender identity, nationality, ethnic origin, religion or belief, disability, age, sexual orientation and identity. Here at DESY, we attach great importance to an appreciative working atmosphere, the equality of all employees and a better work–life balance.

Since September 2021, the Start-up Labs Bahrenfeld, a project jointly managed by DESY, Universität Hamburg and the City of Hamburg, has been the new place for science entrepreneurship on DESY's research campus. The variety of fields covered by our young entrepreneurs is huge, ranging from synchronisation systems to individualised tests for diagnosing cancer.

DESY and the Hamburg University of Applied Sciences (HAW Hamburg) agreed on a new strategic Cooperation for Application and Innovation (KAI) with a focus on joint research and development programmes, dual education as well as innovation and technology transfer. KAI will help shape Hamburg's structural transformation into a science and innovation metropolis in northern Germany.

Finally, I would like to mention our public outreach format "Wissen vom Fass" (Science on tap), in which scientists from Universität Hamburg and DESY explain science topics to the public and answer exciting questions from the world of research. This year, the event was purely digital, but it was just as entertaining and enjoyable for everyone as before.

In these challenging times, I would like to thank our staff and all our national and international users and partners for their valuable contribution to DESY. Please remain very careful in this tricky winter period and beyond. I wish you all the best!

Helmut Dosch
Chairman of the DESY Board of Directors

Particle physics at DESY

Introduction

Dear Colleagues and Friends of DESY,

It is my great pleasure to address you all, for my first time introducing the 2021 *DESY Particle Physics* annual report. This highlights brochure will give you an excellent overview of the major achievements and ongoing efforts of the particle physics division at DESY. Browsing through one of the final drafts filled me with excitement about the many excellent results that were produced in 2021, under unusually difficult circumstances!

And a difficult year it was indeed – the second COVID-19 year with all the ensuing restrictions on our social and work life. I am impressed how well our people at DESY and our many international partners coped with these tough conditions, and I sincerely hope for more opportunities to interact in person in 2022.

Figure 2

Farewell cake for Ties Behnke

On the structural side, DESY has entered the fourth programme-oriented funding period (PoF IV) of the Helmholtz Association, which will take us through the next seven years. In 2020, the DESY particle physics division passed the evaluation of its proposal with flying colours, one important element being a new subtopic structure for our scientific activities that does not focus on the facilities at which we work (LHC, Belle, etc.). Instead, three guiding themes that touch on many of our activities were introduced, which will accompany us for the coming years: i) Higgs physics and fundamental interactions, ii) new particles and phenomena and iii) cosmology and the dark sector of the universe. I am looking forward to truly living this new structure in the next years.

The year 2021 brought numerous achievements and outstanding results – to mention a few: At the Large Hadron Collider (LHC) at CERN near Geneva, Switzerland, the experiments ATLAS and CMS were in Long Shutdown 2 for almost two years and continued to produce important publications based on the 140 fb^{-1} of data collected during LHC Run 2. Since autumn 2021, the accelerator and the detectors are being brought back to life, and I look forward to the more than doubling of the LHC data set in the next four years at a new record-high centre-of-mass energy. However, the next shutdown of the LHC is already on the horizon. In 2026, the upgrade to the High-Luminosity LHC (HL-LHC) will begin, and our ATLAS and CMS groups have been very busy preparing the DESY contributions: The R&D work and prototyping for the two silicon tracker end-caps were mostly concluded, and the production chains for the modules, the larger mechanical structures where they are mounted, the readout electronics and services are to a large extent finalised – ready for production in the new Detector Assembly Facility (DAF) at DESY.

At the Belle II experiment at the SuperKEKB collider at KEK in Japan, despite issues with machine backgrounds, several luminosity world records could be achieved. DESY employees were busy with the physics exploitation of the data and with services to the experiment. We also prepared the assembly of the new pixel vertex detector, which will be installed in the 2022/2023 shutdown.

Figure 1
Beate Heinemann

Particularly good news comes from our on-site activities, the axion search experiments and LUXE: The installation of ALPS II in the tunnel of DESY's former HERA collider was successfully concluded with the first complete cooldown of the magnets to 4 K in December 2021. The BabyIAXO collaboration finished its conceptual design report, and preparatory work for the construction of the experiment in the HERA South hall has started. For MADMAX, major milestones were the finalisation of the conceptual design report for the cryogenic platform in the HERA North hall and the CERN approval of prototype tests in CERN's MORPURGO magnet. Finally, the collaboration proposing the laser-and-XFEL experiment LUXE, which aims to study the quantum electrodynamics (QED) vacuum in a new regime, published its conceptual design report.

On the theory side, a large number of very interesting publications was completed, and our theorists have been instrumental in exploring short- and long-term opportunities. I am also thrilled that the funding for the building for our outstanding theory group, the Wolfgang Pauli Centre, is – finally! – secured, and preparations for the construction are proceeding.

Finally, important advances were made in the areas of detector development and scientific computing. Our R&D effort on CMOS detectors and our activities in quantum computing and machine learning, for example, made impressive progress. And, despite the pandemic, we were able to provide test beams to more than 300 users and hosted two teams of high-school students in the context of the Beamline for Schools competition.

In summary, we are progressing well, and I am confident that, in 2022, we will be able to harvest the fruits of our long-term investments and hard work of the past. This harvest would never have been be possible without all the people in the DESY particle physics division, who, despite difficult conditions, have worked so hard and continue to show so much effort, ingenuity and creativity. Thank you very much! I would particularly like to thank Ties Behnke for his excellent services as interim director of the division in 2021. He took over from Joachim Mnich only slightly more than a year ago, and he steered us all through the very demanding year and gave a number of important impulses to the division, on which I am more than happy to build.

Let me end by saying that I am very much looking forward to working with all of you, at DESY and in our partner institutions around the world, and to shaping the future of our research centre together with you.

Yours sincerely,

Beate Heinemann
Director in charge of Particle Physics

News and events

A busy year 2021

January

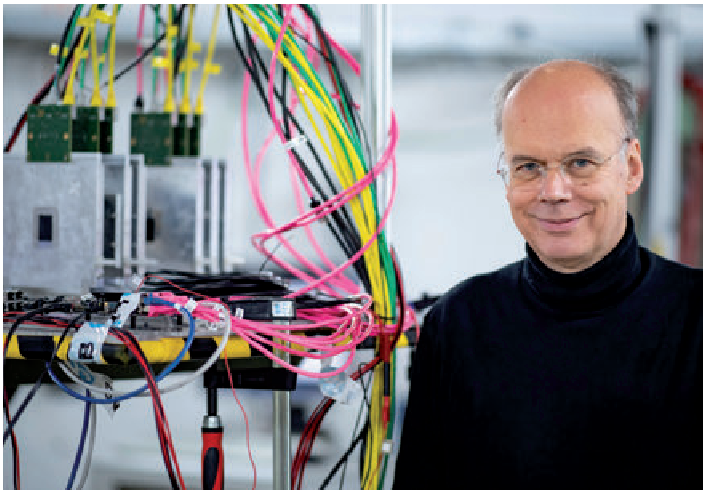
Geneva calling

Joachim Mnich was Director in charge of Particle Physics at DESY for 12 years. From January 2021, he took up a new job as Research Director at CERN near Geneva, Switzerland. He will be in charge of the broad spectrum of experiments at the research centre, including the experiments at CERN's flagship accelerator, the Large Hadron Collider (LHC), which is currently undergoing a significant upgrade.

Joachim Mnich

Ties Behnke takes over as director

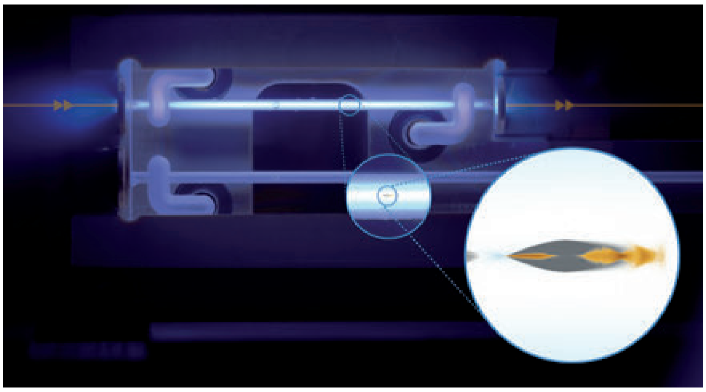
Ties Behnke took over as interim Director in charge of Particle Physics from 1 January 2021. He held this position until a successor for Joachim Mnich was found. Ties Behnke has been a leading scientist in particle physics at DESY since 1998, focusing on electron–positron colliders and detector development. He is also the spokesperson of the Helmholtz programme "Matter and Technologies".



Ties Behnke

Flattening the wave

The technology of plasma-based acceleration promises to deliver a new generation of powerful and compact particle accelerators. An international team of researchers achieved a major milestone at the FLASHForward experiment at DESY: The team created precisely tailored particle bunches to drive a plasma accelerator. For the first time, the researchers were able to preserve a sharp energy spectrum within the accelerated particle bunch while simultaneously accelerating particles with record-high energy efficiency – both prerequisites for a sustainable application in compact next-generation colliders and brilliant photon sources.

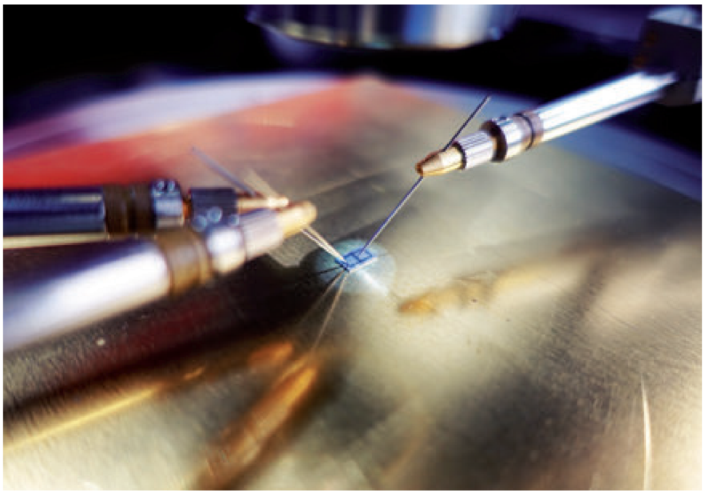


A 50-mm-long plasma accelerator module in operation

May

CMS pushes the precision frontier on luminosity

With major contributions from DESY physicists, the CMS collaboration at the LHC at CERN published a new measurement of a crucial value, the integrated luminosity, taking precision to a new level. The new luminosity measurement with an uncertainty of 1.2% is the most precise result achieved at a high-energy and high-luminosity hadron collider experiment so far.



Silicon sensor for the CMS fast beam condition monitor (BCM1F) during characterisation at DESY

EU project for innovative particle detectors

A new EU project called AIDAinnova (Advancement and Innovation for Detectors at Accelerators) will develop a variety of innovative particle detector technologies for experiments at future colliders. The 45 project partners from academia, research and technology institutions and industry were represented at a virtual AIDAinnova kick-off meeting, where each of the project's work packages (detector facilities, silicon detectors, calorimeters and particle identification, gaseous and large cryogenic detectors, backbone technologies and management, outreach and innovation activities) convened at dedicated sessions to present their work plan or kick off the groundwork for future developments.

A total of 45 partner institutions are involved in the AIDAinnova project.

Strengthening the bond

Traditionally, DESY and the High Energy Accelerator Research Organization KEK in Tsukuba, Japan, have enjoyed close and intensive cooperation based on a framework agreement concluded in 2000. DESY and KEK have many overlapping research topics, including, in particle physics, DESY's contribution to the Belle II experiment at the SuperKEKB collider at KEK and joint work on the ATLAS detector at the LHC at CERN. Both centres are also operating photon sources and are very active in the development of future accelerators. To meet the changing focus of research over time, the directors of KEK and DESY signed a new framework agreement for their cooperation in May.

KEK Director Masanori Yamauchi, DESY Director Helmut Dosch

Vibrating science

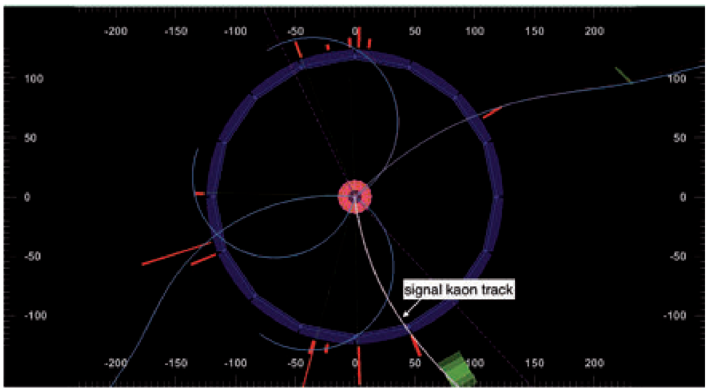
In May, a special vehicle visited DESY: a Vibrotruck, which put the ground in motion for a study. The new WAVE collaboration of Universität Hamburg, DESY and the German Research Centre for Geosciences (GFZ) took advantage of this, using a new measurement method that employs telecommunications optical fibres to localise vibrations down to metre precision. Weeding out unwanted vibrations could be a big plus for the DESY research campus.

The WAVE collaboration used telecommunications fibres to localise vibrations generated on the DESY campus by a Vibrotruck.

June

Kaon is key

Researchers from DESY working on the Belle II experiment at KEK in Japan published the fourth Belle II paper since the beginning of data taking. They studied the decay of *B* mesons produced in collisions at Belle II into kaons and neutrinos – a rare but highly interesting decay. If nature does not behave the way theory predicts, scientists could see it in this process. So far, they have found no deviation from predictions.

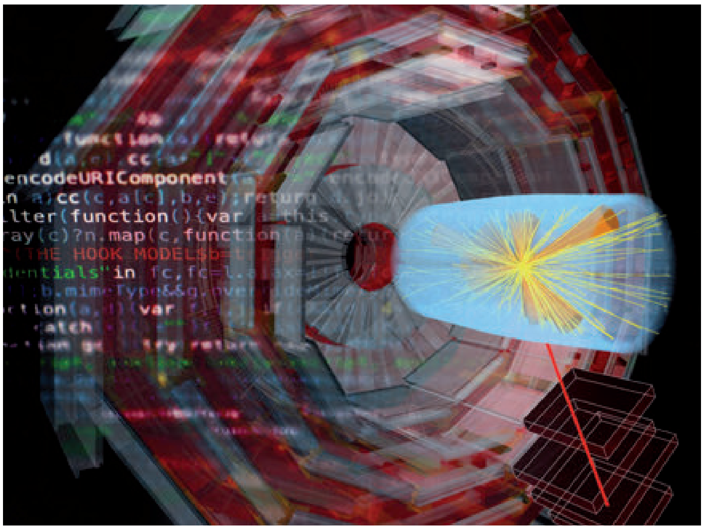


Rare *B* meson decays: DESY scientists look for events like these in the Belle II detector.

The publication is a milestone in the physics history of Belle II because it is the first based on data collected with the complete detector. Previous analyses used collisions collected by Belle II in a preliminary stage, in particular without the new pixel vertex detector, for whose construction, commissioning and data analysis DESY has leading responsibility.

Fast lane to synthetic data wanted

In addition to experimentally generated data, fundamental research in physics also works with synthetically generated data. Acquisition of such data with currently available simulation methods is extremely time-consuming and ties up immense computer capacity. A new project of DESY, the Helmholtz-Zentrum Dresden-Rossendorf (HZDR) and the HZDR Center for Advanced Systems Understanding (CASUS) in Görlitz is testing an approach with which data on the behaviour of physical systems can be generated more quickly using neural networks. The SynRap project was selected for funding through a competitive process.



Visualisation of an event recorded by a particle detector. The use of neural networks could considerably accelerate the production of synthetic data sets in particle physics.

July

Making research data transparent and sustainably available

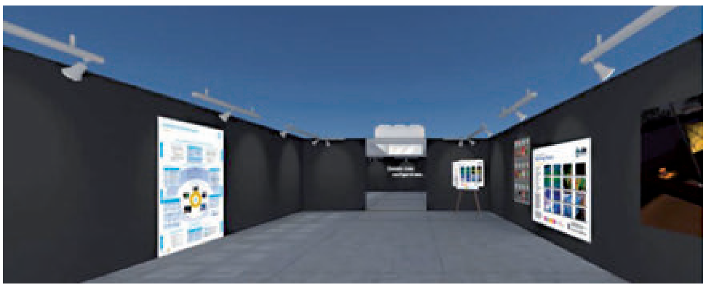
The Joint Science Conference (GWK) of the German federal government and states decided to fund two DESY-led consortia, DAPHNE4NFDI and PUNCH4NFDI, within the framework of the German National Research Data Infrastructure (NFDI). The consortia, which were selected for funding together with eight others, have set themselves the goal of making data from photon and neutron research as well as particle, astroparticle, hadron and nuclear physics and astronomy transparent and permanently available. Both projects will be funded for the next five years. After an evaluation, five more years of funding may follow. Cooperation with other NFDI consortia is envisaged, as are discussions with the ErUM Data Initiative of the German Federal Ministry of Education and Research (BMBF) as well as European projects.

The NDFI connects existing research data services.

EPS-HEP2021 online at DESY – avatars welcome!

From 26 to 30 July, DESY and Universität Hamburg hosted the European Physical Society Conference on High Energy Physics EPS-HEP2021. Due to the COVID-19 pandemic, the conference was organised as a purely online event with plenary talks and parallel sessions for 2000 registered participants.

The conference is a forum for the latest results in particle physics and neighbouring fields. The recent hints at anomalies in the *b* sector were the subject of an intense exchange of facts and ideas. Results from the LHC experiments were presented covering a wide range of science topics, from searches to precision measurements. DESY and Universität Hamburg will also host the next EPS-HEP conference in 2023, this time as an in-person conference.

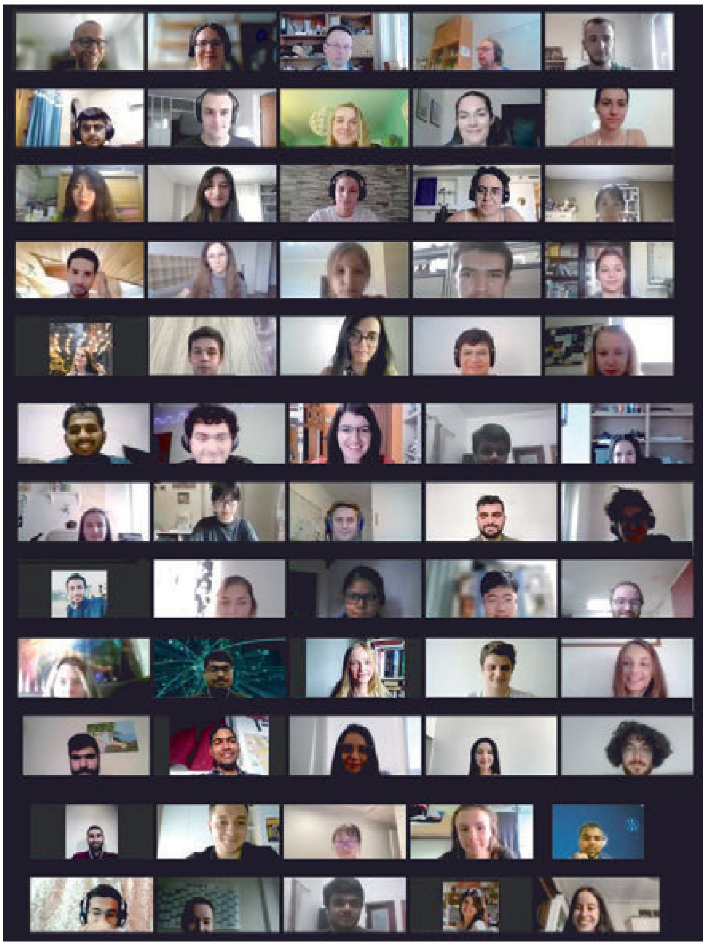


At EPS-HEP2021, the traditional poster session was moved to a virtual exhibition system where presenters could interact with viewers in real time.

"Summies" in the city

Almost 80 students of physics and related natural sciences took part in DESY's summer student programme 2021. The majority of them participated remotely using online tools due to the COVID-19 pandemic, while seven students were integrated in the research groups on the DESY campus in Hamburg.

The DESY summer student programme has been running for several decades and is one of the largest of its kind in Europe, offering insights into particle physics, photon science, accelerator technology, computing and astroparticle physics. The programme includes a lecture series introducing the main areas of research at DESY. Because of the online nature of the 2021 event, the lecture programme was open to everyone, resulting in one of the largest attendances on record with several hundred participants from around the globe.



This year, the "summies" were given a virtual welcome.

August

CoVis – a new app for COVID-19 risk assessment

From theoretical physics to entrepreneurship, propelled by a deadly virus: With his spin-off company, DESY physicist Ayan Paul launched a new app against COVID-19. The app CoVis combines public data with personal information and location, providing users with a highly individualised assessment of their current risk to contract COVID-19, including recommendations for action.

CoVis uses robust and explainable artificial intelligence to predict outbreaks and detect anomalies in disease spread using publicly available data, latest study results and other existing medical knowledge. Combined with personalised information about age, preexisting conditions and movement habits, CoVis helps users to make informed choices about which areas or places to avoid and when.

The new CoVis app is available in Germany and the USA for iOS and Android.

DESY particle physicist and entrepreneur Ayan Paul

DESY signs Diversity Charter

By signing the Diversity Charter ("Charta der Vielfalt"), DESY became part of Germany's largest diversity network. The Diversity Charter is an initiative that aims to promote diversity in companies and institutions. Since its inception in 2006, it has been signed by over 4500 organisations with a total of more than 14.6 million employees.

DESY stands for open-mindedness and tolerance. It is committed to a diverse, prejudice-free working environment and appreciates all employees regardless of their gender and gender identity, nationality, ethnic origin, religion or belief, disability, age, sexual orientation and identity.

charta der vielfalt
UNTERZEICHNET

September

"Urknall unterwegs" – Big bang on the go

In September, a mobile scientific exhibition started touring through Hamburg's districts with the aim to explain the complex world of particle physics in a fun and interactive way to interested citizens. Young and old were invited to a journey through time and space from today back to the big bang and to learn how particle physics revolutionised our understanding of the universe.

Exhibition "Big bang on the go" in Hamburg

Beam us up, DESY!

Prevailing against 289 competitors and one pandemic, the two winning teams of the international Beamline for Schools competition 2021 arrived at DESY in Hamburg in September to carry out their experiments at the DESY II Test Beam Facility. The team Teomiztli, comprising seven students from Mexico City's Escuela Nacional Preparatoria "Plantel 2", used the electron beam to study aspects of the production of Cherenkov radiation in different materials. The team EXTRA, which involved nine students from Liceo Scientifico Statale "A. Scacchi" in Bari, Italy, examined the transition radiation effect, where X-ray photons are generated when high-energy electrons pass through materials of certain optical properties.

The Beamline for Schools competition, usually organised by CERN but hosted at DESY in Hamburg for the third time in a row, encourages teams of high-school students from around the world to submit proposals for experiments that can be performed at a particle beamline.

The Mexican and Italian winning teams of the Beamline for Schools competition pose with DESY firefighters after their fire safety training.

Starting enterprises

Start-ups and established companies in the fields of physics and biophysics found a new home in Western Hamburg in September. The Start-up Labs Bahrenfeld, a project jointly managed by DESY, Universität Hamburg and the City of Hamburg, is the new place for science entrepreneurship on the DESY campus. The innovation centre for deep-tech start-ups will also enhance the profile of the planned Science City Hamburg Bahrenfeld. The Start-up Labs Bahrenfeld were officially opened on 20 September with laboratories, workshops, offices and meeting rooms, covering an area of 2700 m^2. Start-ups from DESY photon science were among the first tenants.

The Start-up Labs Bahrenfeld

Science on (digital) tap

At the "Science on tap" event, scientists from DESY and Universität Hamburg talk about their everyday work, usually in bars and pubs. In 2021, the popular talks took place online because of the pandemic – a superspreading event of a different kind. Five videos are available online, offering fascinating insights into various research areas, from particle physics through communication science to virology, and answering all kinds of questions. Whether online or offline – such entertaining knowledge transfer from scientific experts to the interested public is more important than ever.

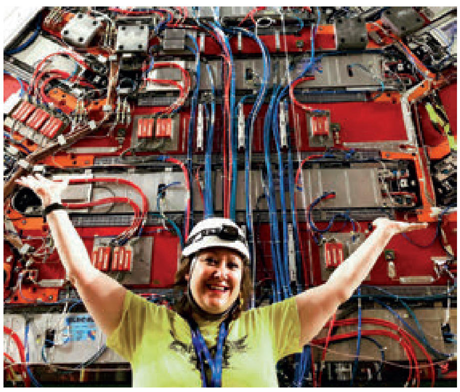
When brains merge...

The new strategic Cooperation for Application and Innovation (KAI) of DESY and the Hamburg University of Applied Sciences (HAW Hamburg) will focus on cooperative degree programmes and teaching, research and development as well as innovation, technology and knowledge transfer. KAI is to strengthen the joint training of urgently needed highly qualified engineers and scientists. It will help shape Hamburg's structural transformation into a science and innovation metropolis in northern Germany, through applied research and by developing sustainable and digital technologies. The City of Hamburg supports the cooperation with start-up funding of 120 000 euros.

From left: DESY Director Helmut Dosch, Hamburg's Science Senator Katharina Fegebank and HAW Hamburg President Micha Teuscher at the launch of the cooperation KAI

October

Freya Blekman joins DESY



Freya Blekman in front of the CMS detector

On 1 October, experimental particle physicist Freya Blekman took up her new position as lead scientist in the DESY CMS group. Born in the Netherlands, she came to DESY from the

Free University of Brussels following a joint appointment with Universität Hamburg within the Helmholtz Distinguished Professorship programme. In addition to her research, Freya Blekman pursues innovative teaching concepts and is known for communicating her research on social media. On Twitter, she is among the top ten most active female physicists in the world. In 2016, she received the Outreach Annual Award from the Belgian Academy of Sciences.

Distinction for Albrecht Wagner and Jochen Schneider

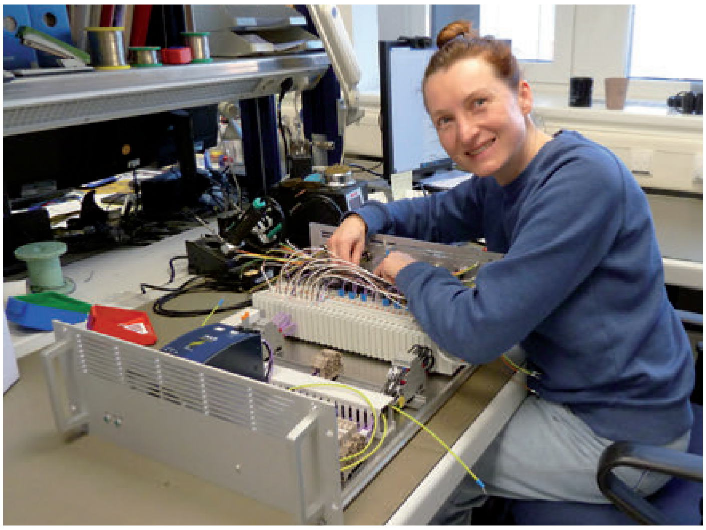
At the 2021 DESY Science Day, Albrecht Wagner and Jochen Schneider – two outstanding personalities who have had a significant impact on the development of DESY – were awarded the DESY Golden Pin of Honour. Wagner was DESY Research Director from 1991 to 1999 and Chairman of the DESY Board of Directors from 1999 to 2009. Schneider was DESY Director in charge of Photon Science from 2000 to 2007. Both were pioneers in a special time after the sudden death of DESY Director Bjørn H. Wiik in 1999. They managed to keep the research centre thriving with a sustainable future – the results of their efforts are still visible today.

DESY Director Helmut Dosch (centre) congratulates Albrecht Wagner (left) and Jochen Schneider (right) at the presentation of the DESY Golden Pins of Honour.

November

First-class DESY trainee

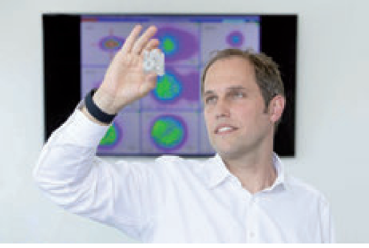
Raphaela Renner, freshly qualified electronics technician for devices and systems, was one of three DESY apprentices officially honoured as best trainees in their fields, in this case by the Hamburg Chamber of Commerce. DESY itself was honoured once again for outstanding achievements in dual training.



Raphaela Renner is amongst Hamburg's best trainees.

Surfin' electrons

DESY physicist Jens Osterhoff received the 2021 Bjørn H. Wiik Prize in recognition of his outstanding contributions to the field of plasma acceleration. Under his leadership, a Helmholtz Young Investigator group in the DESY particle physics division started to carry out research into plasma accelerators, a new generation of accelerators that are much more compact and inexpensive than conventional devices, yet extremely powerful.



Bjørn H. Wiik Prize 2021 laureate Jens Osterhoff with a plasma cell

PhD Thesis Prize 2021

The PhD Thesis Prize 2021 of the Association of the Friends and Sponsors of DESY (VFFD) was awarded in equal parts to Svenja Lehmann and Johannes Michel. Lehmann, who received the prize for her thesis "Oblique-incidence deposition of ferromagnetic thin films and their application in magnetoresistive sensors", went on to recruite new young scientists as a physics teacher on the west coast of Schleswig-Holstein. Michel, now a post-doctoral researcher at MIT in the USA, received the award for his thesis "Factorization and resummation for precision physics at the LHC". One of the highlights of his thesis was the generalisation of a famous, decade-old factorisation theorem, which made it much more powerful and more widely applicable.

Svenja Lehmann and VFFD Board member Wilfried Buchmüller

Johannes Michel

Hamburg Prize for Theoretical Physics 2020 and 2021

For their remarkable contributions to theoretical physics, Russian–American researcher Eugene Demler, the 2021 laureate, and Russian researcher Valery Rubakov, the 2020 laureate, were honoured with the Hamburg Prize for Theoretical Physics by the Joachim Herz Foundation in cooperation with the Wolfgang Pauli Centre of DESY and Universität Hamburg and with the clusters of excellence CUI: Advanced Imaging of Matter and Quantum Universe. The 2020 award ceremony had been postponed due to the COVID-19 pandemic.

Demler, a former member of Harvard University in the USA, now at ETH Zürich in Switzerland, received the 2021 prize for his research on quantum matter. Rubakov, a scientist at INR Moscow and professor at Lomonosov Moscow State University, was honoured with the 2021 prize for his contributions to various topics in quantum field theory, particle physics and cosmology.

From left: Presenter Ralf Krauter with Eugene Demler, recipient of the Hamburg Prize for Theoretical Physics 2021, and Valery Rubakov, laureate 2020

December

New Emmy Noether group in DESY theory

Theoretical physicist Till Bargheer received 1.5 million euros through an Emmy Noether grant from the German Research Foundation (DFG) to perform his research programme within the DESY theory group. The grant allows Till Bargheer to lead his own Emmy Noether Independent Junior Research Group "Solving Field Theory with Integrability", which involves three PhD students and two postdoctoral researchers. Over six years, Bargheer and his team will probe the uncharted parts of quantum field theory using powerful methods from the theory of integrable models.

Emmy Noether Independent Junior Research Group leader Till Bargheer

ALPS magnets cooled down

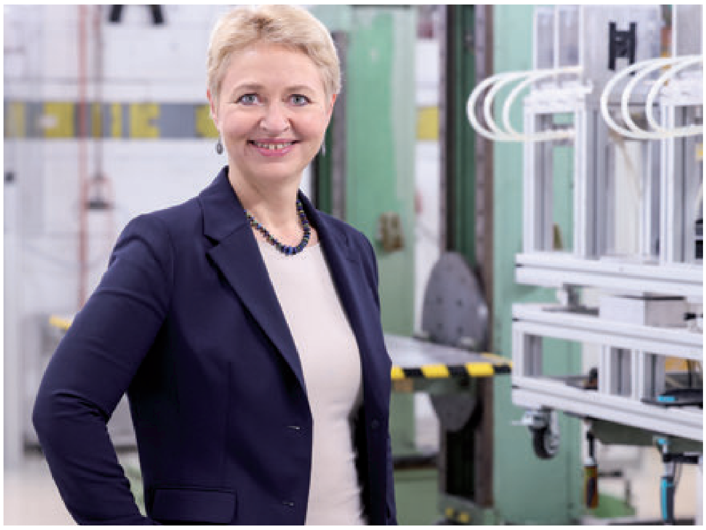
The "light-shining-through-a-wall" experiment ALPS II at DESY passed the next milestone: The superconducting magnets used in the experiment were cooled down to their operating temperature of -269°C. After an interruption of more than 14 years, helium once again flowed through the tunnel of DESY's former electron–proton collider HERA, which houses the experiment, marking an important step in the commissioning of ALPS II.

Just over a year after the last superconducting ALPS magnets were installed in the tunnel, -269°C helium flowed through the magnet chain.

Beate Heinemann – DESY's first female director

In December 2021, the DESY Foundation Council appointed particle physicist Beate Heinemann, a lead scientist at DESY and professor at the University of Freiburg, as Director in charge of Particle Physics. She will succeed Joachim Mnich and interim Director Ties Behnke on 1 February 2022.

Beate Heinemann was born in Hamburg and took her first career steps at DESY. She then joined the University of Liverpool in the UK before becoming a professor at the University of California, Berkeley, in the USA, working on the ATLAS experiment at CERN, where she served as deputy spokesperson. She is now the first woman on the DESY Directorate.



Beate Heinemann, the new Director in charge of Particle Physics and the first woman on the DESY Board of Directors

Experimental particle physics

Physics with protons has been at the heart of DESY’s particle physics activities since the start-up of its former electron–proton collider HERA in 1992. Today, the cornerstones of DESY’s proton physics programme are its ATLAS and CMS groups, which are involved in a large variety of developments at the Large Hadron Collider (LHC) at CERN, from hardware design to data analysis.

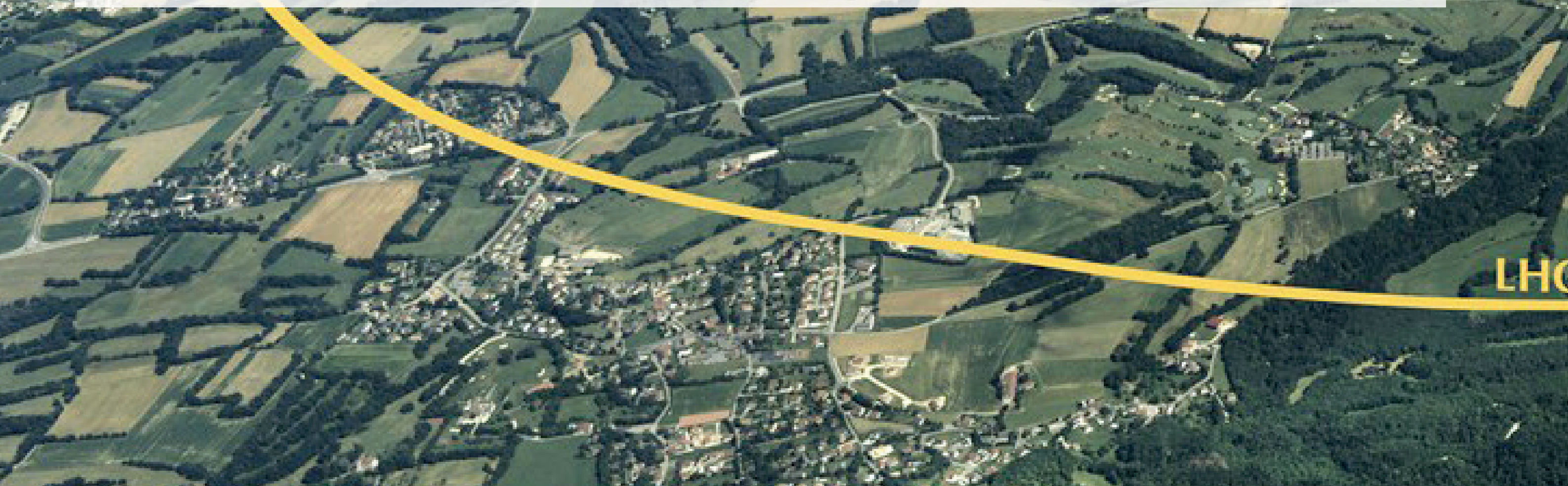
Since its discovery, the Higgs boson has been an important focus of research. Unravelling its precise properties constitutes one of the main activities at the LHC experiments. This includes studying its couplings (p. 34) and investigating complex scalar sectors with dark matter (p. 35). Another focus of the LHC is the heaviest particle of the Standard Model, the top quark. Here, the precision of fundamental constants of the strong force has been improved (p. 21), a new professorship was established (p. 29), and new interactions have been probed (p. 22). Other studies explored the structure of the proton and further properties of the electroweak sector (p. 26).

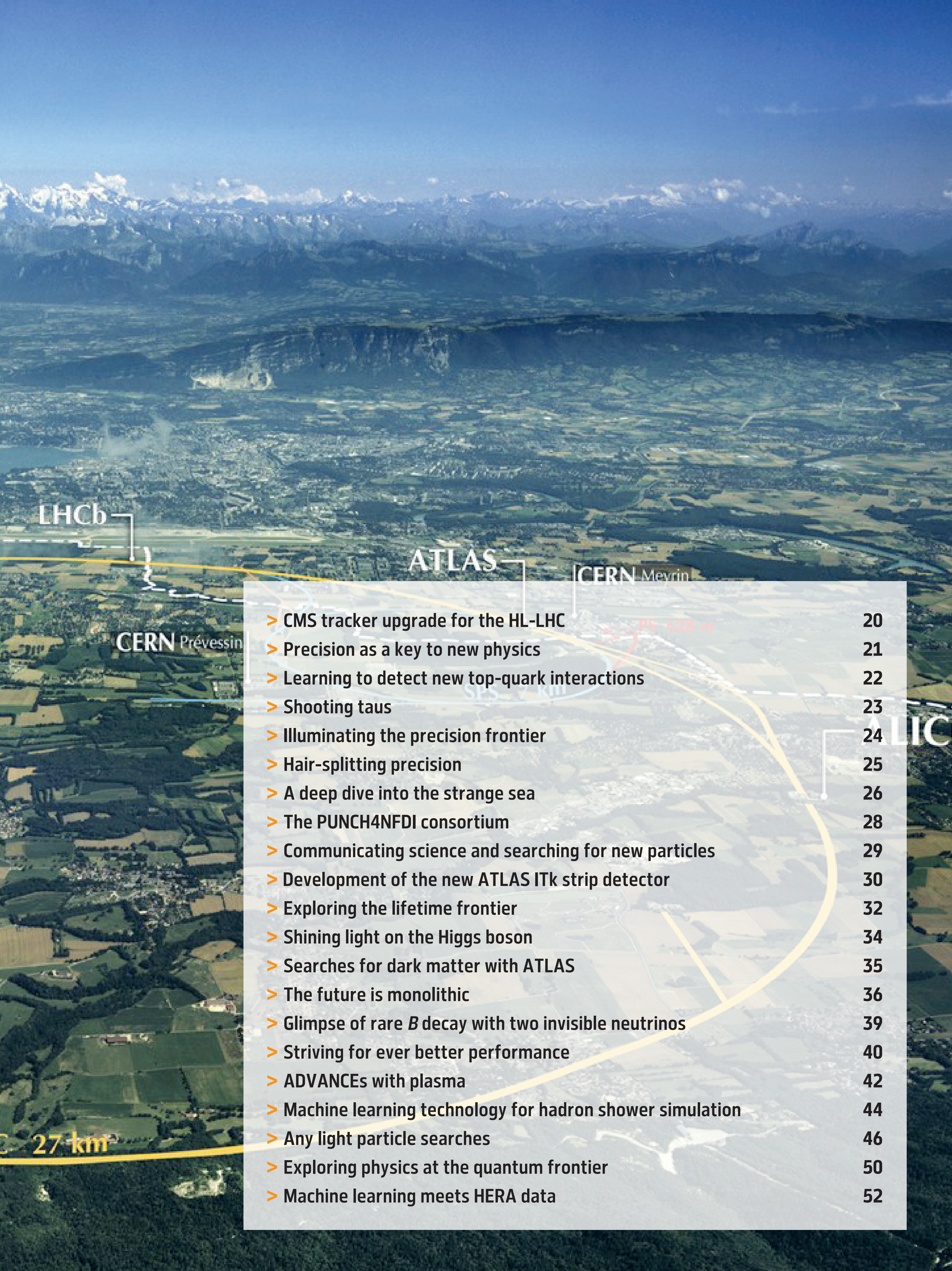
At the same time, the DESY LHC groups are preparing for the future LHC upgrades – in particular, the high-luminosity upgrade (HL-LHC) foreseen for the years after LHC Run 2. Activities at DESY for these upgrades include the development of new detectors (p. 30 and p. 36), improved measurements of the luminosity (p. 24) and the development of tracker technology (p. 20 and p. 25).

Physics with lepton beams – and the R&D work for the necessary accelerators and detectors – constitutes the second pillar of DESY’s particle physics activities. The focus here is on the upgraded SuperKEKB accelerator with the Belle II experiment at the Japanese national particle physics laboratory KEK. The performance of the experiment is continuously being improved (p. 40), which allows for new results, for example involving *B*-meson decays (p. 39).

DESY has also broadened its activities in the field of axion-like particles (p. 46). The construction of the ALPS II experiment is proceeding as foreseen, while preparations started for two new experiments, IAXO and MADMAX. Furthermore, the LUXE collaboration plans to scrutinise quantum electrodynamics in the non-linear regime (p. 50) and the ADVANCE lab develops plasma acceleration (p. 42).

Finally, machine learning and other novel techniques are taking hold in particle physics. They help to identify tau leptons (p. 23), to search for late decays (p. 32), to simulate hadronic showers (p. 44) and to present old HERA data in a new light (p. 52).





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CMS tracker upgrade for the HL-LHC

When on-module p_T discrimination becomes reality

In order to cope with the higher data rates during the High-Luminosity LHC (HL-LHC) era, the upgraded CMS outer tracker will be based on a new module concept with on-board particle momentum discrimination, which will allow it to contribute to the CMS trigger system. Every module will be made of two vertically stacked silicon sensors, either a macropixel sensor and a strip sensor (PS) or two strip sensors (2S). The modules will be equipped with dedicated front-end electronics to correlate the signals from both sensors, exploiting the strong magnetic field of CMS to select high-transverse-momentum particles, and send the corresponding information to the CMS Level-1 triggering system. The DESY CMS group is preparing for the production of about 1250 PS modules and working on the development of the data-processing system.

Assembling modules

The DESY CMS group is committed to assembling about 1250 PS modules and is leading the development of a robot-assisted (automated) assembly procedure. The resulting object is a stack of silicon sensors separated by electrically isolating spacers and glued onto a thin carbon fibre support. The next step is to attach the module electronics. Four printed circuit boards are placed on, glued and connected to the periphery of the silicon sensor stack: the power hybrid for module powering, two front-end hybrids for sensor readout and the readout hybrid for optical data transmission. In 2021, the DESY CMS group reached a first milestone by assembling 2.5 fully functional PS modules.

Testing modules

The group also plays a leading role in the development of the data-processing system chosen for both the module prototyping and the production phase. The DESY CMS group is involved in the design and development of field-programmable gate array (FPGA) firmware needed for electrical testing of the individual PS module components and for optical readout of the full modules in the lab tests or beam tests. In addition, the group contributes to the development of the data acquisition and control software framework Ph2ACF used for module prototype testing and for both the production phase and the final detector operation.

The group has played a decisive role in reaching another milestone: the firmware and software implementation of the optical readout of modules equipped with the CERN low-power gigabit transceiver (lpGBT) chip and with the versatile link plus transceiver (VTRx+) module. Firmware and software are now used to test all the individual components and assembled modules in the collaborating institutes around the world.

Finally, in 2021, the DESY CMS group successfully collected the first set of PS module data in a test beam campaign. The assembled PS module first underwent extensive lab tests and was then brought to the DESY II Test Beam Facility, where it was characterised under electron beam exposure (Fig. 1). Configurations such as the geometrical orientation, the sensor bias voltage or the readout settings were varied in order to study the module's particle detection and momentum discrimination efficiencies. The data are currently being analysed with the objective of validating the design of the sensor and front-end electronics and gaining insights into the overall operation and performance of the module.

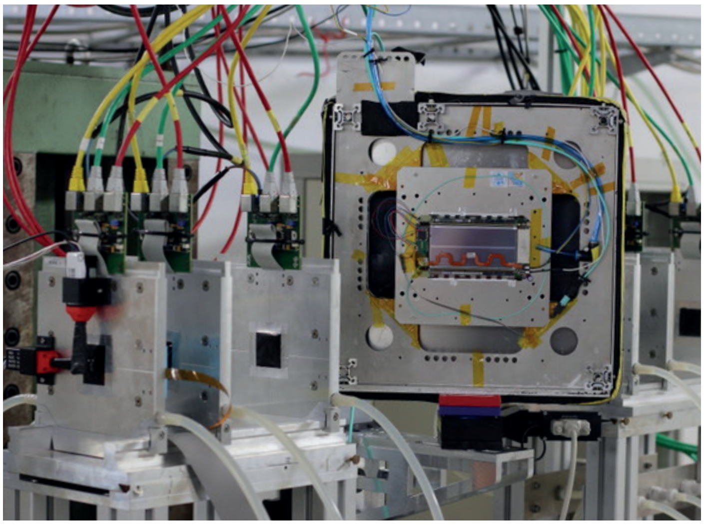

Figure 1

First PS module in the DESY test beam

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Precision as a key to new physics

Constraining the Standard Model and beyond using jets at CMS

For the first time, by analysing the rates of jet and top-quark production at the LHC, DESY CMS physicists extracted the fundamental parameters of the Standard Model, simultaneously imposing constraints on new physics. As a result, the description of the proton structure is significantly improved and the obtained values of the strong coupling constant and of the top-quark pole mass break the current level of precision achievable at a hadron collider. At the same time, the first unbiased limit on the scale of novel contact interactions is achieved. The work is supported by the Helmholtz W2/W3-123 programme.

Best precision for QCD

In the Standard Model of particle physics, the fundamental building blocks of nuclear matter, quarks and gluons, together called partons, are subject to the strong interaction, described by quantum chromodynamics (QCD). Once kicked out of e.g. a proton, partons form collimated sprays of hadrons, called jets. By measuring the jet rates in proton–proton collisions, it is possible to extract the value of the strong coupling constant and the momentum distributions of the partons in the proton.

The most recent measurement [1] of jet production at the LHC at a centre-of-mass energy $\sqrt{s}$ = 13 TeV in the CMS detector is the most precise of its kind and reaches jet momenta up to 3 TeV. This measurement was interpreted in QCD at next-to-next-to-leading perturbative order. As a result, the precision of the gluon distribution in the proton was improved by more than a factor of 2 (Fig. 1). Simultaneously, the value of the strong coupling constant at the scale of the Z-boson mass was determined as $\alpha_S (m_Z)$ = 0.1170 ± 0.0019. This is the most precise single-experiment measurement at a hadron collider to date.

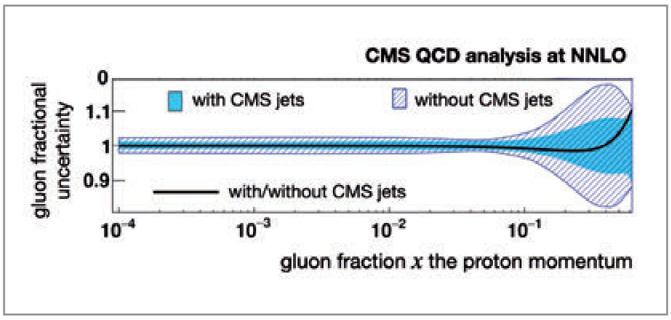

Figure 1

Fractional uncertainty in the gluon distribution in the proton before and after considering the CMS measurement [1] of jet rates at 13 TeV

New physics and Standard Model "in one go"

Jets are also probes for physics beyond the Standard Model – a fundamentally new interaction setting in at very high energy scale Λ. New physics would show up as a deviation of the observed jet rate from the QCD expectation. The challenge is that the observed rate is a mixture of the new interaction and the QCD process, and the interpretation would be biased by assumptions on QCD parameters. The DESY CMS scientists have resolved this long-standing problem. The rates of jets and top quark-antiquark pairs at CMS were interpreted using a model where QCD was modified by the effective couplings of new physics. As a result, the parton distributions in the proton, the top-quark mass and the strong coupling constant were obtained with best precision, together with the effective couplings of new physics, so that the unbiased constraints are obtained for the first time (Fig. 2).

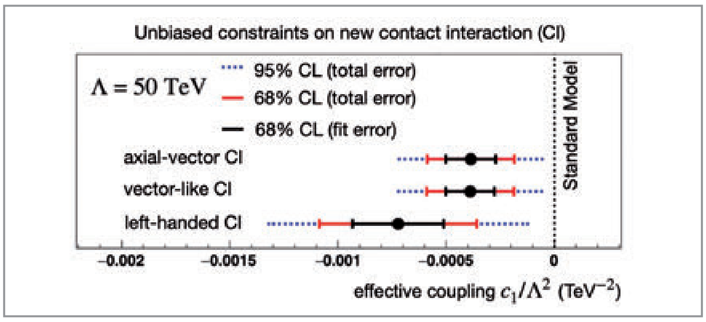

Figure 2

Ratio of the effective coupling to the energy scale of new physics, squared [1]

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Reference:

[1] CMS Collaboration, JHEP 02, 142 (2022)

Learning to detect new top-quark interactions

Probing new phenomena in top-quark couplings with machine learning

Using the full set of LHC data at 13 TeV, the DESY CMS group has successfully performed original research looking for new top-quark electroweak couplings within the framework of an effective field theory (EFT). Targeting *Z*-associated top-quark production, an analysis was designed based on machine learning (ML) techniques to enhance the sensitivity to the corresponding EFT operators. Trained to distinguish between Standard Model (SM) processes, a multiclass neural network optimally defined three subregions enriched in tZq, $t\bar{t}Z$ and background events. Additional neural networks were trained to separate, in the $t\bar{t}Z$ and tZq subregions, the SM scenario from cases where one or more EFT operators are activated. This was the first time that ML techniques accounting for the interference between EFT operators and the SM amplitude were used in an LHC analysis.

Ever since its discovery in 1995, the top quark has been considered a probe of choice for revealing physics beyond the SM. For instance, because of its high mass, the top quark has a Yukawa coupling close to unity, impacting the electroweak sector significantly through loop corrections, and may couple preferentially to undiscovered heavy states. However, searches for new massive particles at the LHC have so far been inconclusive. Model-independent measurements within the EFT framework are thus becoming increasingly important to make the most out of the wealth of precision measurements carried out at the LHC.

The DESY CMS analysis searched for anomalies in top-quark interactions with the Z boson, using an EFT framework [1]. The cross section measurements of the rare associated production modes of these two particles ($t\bar{t}Z$ and tZ) were statistically limited until recently. These interactions are among the least constrained by the available data in the top-quark sector, despite being modified in numerous models beyond the SM. Using the full LHC Run 2 data set, this study targeted favourable final states with multiple electrons and muons. It sets some of the tightest constraints to date on five generic types of EFT interactions that could substantially modify the characteristics of associated top–Z production, while having negligible or no effect on background processes.

The key feature of this work is the heavy use of ML techniques to improve the sensitivity to new couplings. First, to define regions enriched in the processes of interest, a multiclass neural network was trained to discriminate between different SM processes. Subsequently, several binary neural networks learned to separate events generated according to the SM from events that include EFT effects arising from one or more types of anomalous interactions. These binary classifiers were used to construct powerful discriminant variables out of high-dimensional input data. Their distributions were fitted to data to constrain up to five types of EFT couplings simultaneously (Fig. 1). The widths of the corresponding confidence intervals were significantly reduced thanks to the optimal combination of the available kinematic information. This result is an important step towards the more widespread use of ML to target EFT effects in order to efficiently explore the enormous volume of LHC data more globally and comprehensively.

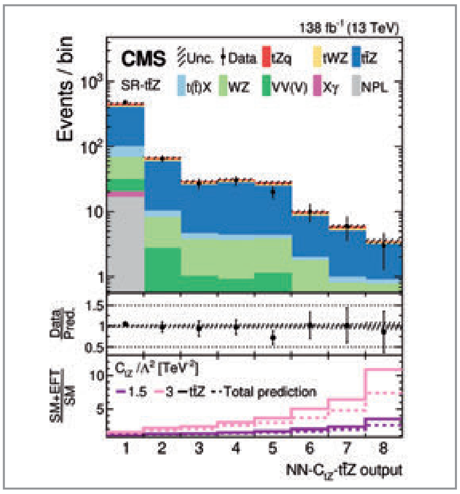

Figure 1
Response of the neural network used to target a specific type of EFT interaction in $t\bar{t}Z$ production. This illustrates the neural network's capacity to isolate potential anomalous effects.

Contact:

This article is written in memory of our dear colleague and friend, Nicolas Tonon (1993–2021), who developed and brought this analysis to success. The text is true to his writing for the *CERN Courier* [2].

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References:

[1] CMS Collaboration, JHEP 12, 83 (2021)
[2] CERN Courier, "Learning to detect new top-quark interactions", 4 October 2021

Shooting taus

It's a hadron… It's a lepton… No! It's a hadronically decaying tau!

The tau lepton plays a crucial role in particle physics as the heaviest lepton in the Standard Model and a key piece of the puzzle in the search for new physical phenomena. It stands out among other leptons in terms of its properties, being the only one that can decay hadronically, but is not particularly easy to catch in the detector. The DESY CMS group, in collaboration with other institutes, contributed to a novel identification algorithm called DeepTau, inspired by the computer vision domain, which goes beyond previous conventional approaches and outperforms them by a large margin.

To understand the properties of nature, scientists rely on already discovered and explored elementary particles as the building blocks for a search beyond what is known. The tau lepton is one of these fundamental particles. It decays to hadrons around 2/3 of the times, producing mostly charged and neutral pions in its decay. This makes hadronically decaying tau leptons (τ_h) easy to confuse with other objects, in particular jets and lighter leptons. Jets are showers of particles mostly originating from gluons and quarks, while electrons and muons can be misidentified due to their Bremsstrahlung radiation.

The main innovation of the DeepTau algorithm lies in approaching τ_h identification by visualising the particles reconstructed in the detector as a 2D image. The image is constructed as centred around the direction of flight of the original particle shower. Figure 1 shows a typical $\tau \rightarrow 3\pi$ decay, with three charged pions clustered together in the blue box. This is in contrast to quark/gluon jets, which generally have broader clusters. DeepTau automates such processes for each proton–proton collision.

This is where computer vision comes into play. DeepTau combines 1D and 2D convolutional layers operating on an image representation of the observed object in the detector. These layers combine low-level information into higher levels, which are then used as a handle to separate tau leptons from jets and light leptons. All with a single, fully automated model!

The DeepTau algorithm significantly improves the performance of τ_h identification by 10–30% compared to the previously used approaches. A new reconstruction algorithm was introduced to complement the improved identification, allowing for more decay channels to be identified. However, good performance is not enough. The model might still learn features in simulation that do not work in reality. The DESY CMS group performed extensive studies to make sure that this is not the case and to correct for any possible discrepancy.

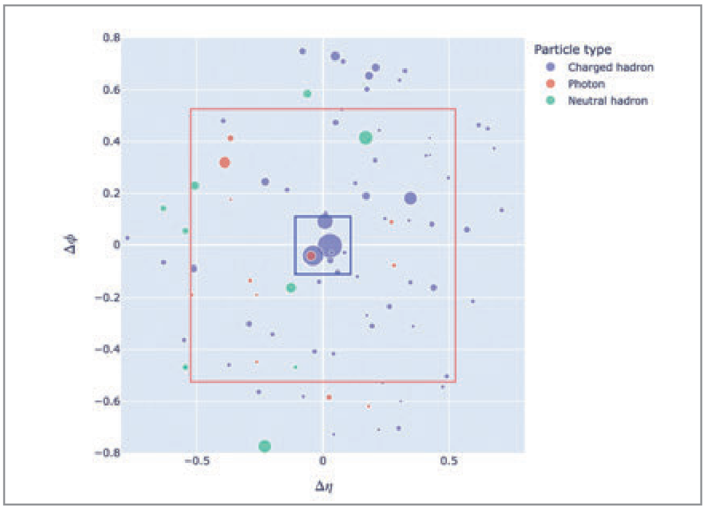

Figure 1

Typical signature in the CMS detector of a $\tau \rightarrow 3\pi$ decay. Each circle represents a different particle, with p_T proportional to the circle size. The red (blue) line represents the isolation (signal) cone. Input features are taken independently from each grid.

Together with its outstanding performance, a vision-driven DeepTau brings hope that the search for new physics will yield new, exciting discoveries.

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[1] CMS Collaboration, arxiv:2201.08458 [hep-ex]

Illuminating the precision frontier

CMS luminosity measured with unprecedented precision

Luminosity is a measure of the particle collision rate in a collider experiment. Its precise value is a crucial ingredient for the operation of the LHC and the experiments as well as for physics data analysis. In 2021, with strong involvement of the DESY CMS group, the CMS collaboration published a new luminosity measurement, taking the precision to a new level. In parallel, in preparation for LHC Run 3, a new refurbished online luminosity detector and beam condition monitor (BCM1F) was built and installed in the CMS experiment.

High-precision luminosity analysis

At the LHC, luminosity is determined from the analysis of van-der-Meer (vdM) scan data. In vdM scans, the event rate is measured as a function of the transverse separation of the two beams (Fig. 1). From the measured beam–beam profile and the beam currents, the luminosity calibration is determined.

So far, typical uncertainties at hadron collider experiments were about 2%, a value already significantly better than originally deemed possible. In 2021, with major contributions from DESY, the CMS collaboration achieved a luminosity measurement with an uncertainty of 1.2%, taking precision to a new level. By applying various novel techniques, several permille-level corrections for residual correlations, non-linearities and time dependencies were determined in order to achieve this most precise result. The measurement, based on data from 2016, the first year of LHC Run 2, is a proof-of-concept for future measurements at the precision frontier.

Upgrade for LHC Run 3

In CMS, several luminosity detectors of different technology are used for redundancy and uncertainty

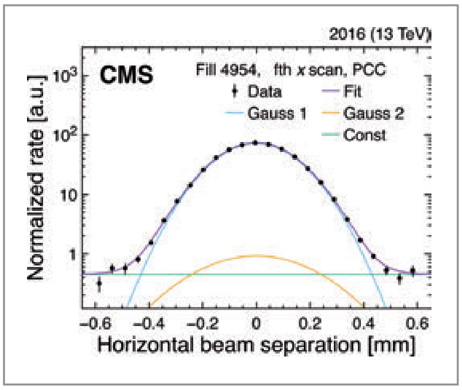

Figure 1
During van-der-Meer scans, the beam axes are separated in transverse direction, and the collision rates are measured. The figure shows the measured rate as a function of the horizontal separation. Taken from [1].

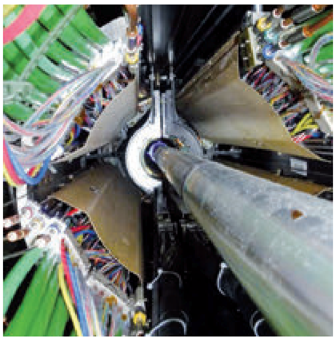

Figure 2
View along the LHC beam pipe towards the centre of the CMS detector. The BCM1F detector is installed very close to the beam pipe within the silver/grey "C-shaped" housing [2].

reduction. The BCM1F detector measures the instantaneous LHC luminosity and beam backgrounds bunch by bunch every 25 ns. The result is delivered in real time to the CMS and LHC control rooms.

BCM1F consists of four "C-shaped" stations, installed very close to the LHC beam pipe at a distance of 1.8 m from the collision point (Fig. 2). For LHC Run 3, starting in 2022, the detector was upgraded with silicon diodes using active cooling and AC-coupled readout. DESY contributed to the detector assembly, sensor testing and installation in the experiment. During the initial LHC test beams in October 2021, the detector worked out of the box. We are now eagerly awaiting LHC beams in 2022 and throughout LHC Run 3.

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References:

[1] CMS Collaboration, Eur. Phys. J. C 81, 800 (2021), arXiv:2104.01927 [hep-ex]
[2] BCM1F Installation in CMS, https://cds.cern.ch/record/2777045

Hair-splitting precision!

First alignment of CMS silicon tracker in preparation for LHC Run 3

The DESY CMS group continued its long-term commitment to the alignment of the CMS tracker in 2021, playing a leading role in the tracker alignment effort during the final countdown to LHC Run 3. Following the reinstallation of the silicon pixel detector in summer 2021, the group was instrumental in deriving the very first tracker alignment after the reinstallation, using cosmic-ray muons collected at 0 T magnetic field, and in the first alignment with collision data of the commissioning period towards LHC Run 3. These early data-taking exercises successfully prepared the ground for a smooth startup of LHC Run 3, later in 2022.

Alignment of the reinstalled pixel detector

In summer 2021, the pixel detector was reinstalled in the CMS experimental cavern after undergoing extensive repairs, which included the replacement of its innermost layer due to radiation damage. The pixel detector, while about the size of a shoebox, contains the impressive amount of 124 million pixels. Thanks to the tiny size of these pixels (100 x 150 μm²!), the position of the hits left by traversing charged particles can be measured very accurately. However, this requires precise knowledge of the position of each of the detector modules on which sets of these pixels are mounted. Determining the position together with the orientation and curvature of the modules is the task of the tracker alignment. The alignment calibration becomes especially relevant after reinstallation when large deviations of the detector modules from their previous positions before the removal can be expected.

Once the pixel detector was in place and ready for commissioning, cosmic-ray muons were recorded at 0 T magnetic field. For each of the hits left in the detector by a cosmic-ray track, the difference between the measured hit position and the one predicted from the track fit, known as track-hit residual, can be computed. The overall spread of the track-hit residuals from a collection of tracks becomes wider if the assumed geometry differs from the real one. By performing a global least-squares minimisation of this quantity, it is possible to update the knowledge on the position of the modules. This precision improves with the number of tracks.

The DESY team was strongly involved in improving the performance from the LHC Run 2-based alignment (Fig. 1, black) via a preliminary alignment step (blue) to a high-precision calibration (red). The very narrow final distribution peaking around 0 indicates that, after the alignment calibration with cosmic-ray tracks and no magnetic field, the module position along the measurement direction is already known with a precision of about 29 μm, which is as narrow as a human hair! This effort paved the way for the final undertaking of 2021, in which the first alignment with collision events after the beginning of Long Shutdown 2 in 2018 was derived, consolidating the alignment workflows towards the start of LHC Run 3.

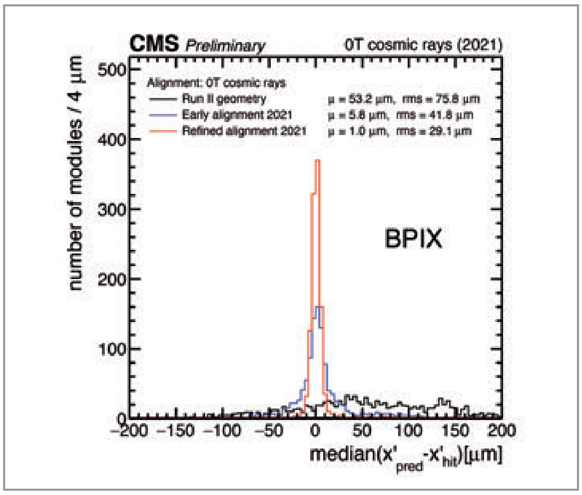

Figure 1

Distribution of median track-hit residuals in the barrel pixel (BPIX) detector, along the local *x'* direction. The tracks were fitted with the last tracker geometry of the previous data-taking period (black) and with the alignment derived in two consecutive steps in 2021 (blue and red). A significant improvement of the local precision is observed when tracks are fitted with the ultimate updated geometry, resulting in a well-centred and very narrow distribution.

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[1] CMS Collaboration, CMS-DP-2021-025

A deep dive into the strange sea

Learning about the structure of the proton using vector boson plus jet processes at the LHC

The proton is made up of quarks and gluons. The quark content is dominated by light (up and down) quarks, but quantum chromodynamics (QCD) predicts that heavier quarks, such as strange quarks, are also present. The heavier quarks are produced as virtual quark–antiquark pairs known as sea quarks, and the extra mass of these quarks means that fewer are expected compared to the light quarks. In 2021, scientists from the DESY ATLAS and CMS groups studied the structure of the proton using data from the production of heavy bosons, *W* and *Z*, in association with jets at the LHC. These data sets threw new light on the strange-quark content of the proton.

Including vector boson plus jet data in QCD fits

Production of heavy vector (*W* and *Z*) bosons in proton–proton collisions is one of the best-understood processes at the LHC. The simplest way to produce the bosons is via the Drell–Yan process: the annihilation of a quark and antiquark. Slightly more complex processes can produce vector bosons in association with hadronic jets ("vector boson plus jet production"). A representative Feynman diagram that contributes to the production of *W* bosons plus jets is shown in Fig. 1. Measuring this process yields information about the quark and gluon distributions within the proton, which provide the incoming partons in the figure. The outgoing quark *q*′ leads to a hadronic jet in the final state.

The quark and gluon distributions cannot be directly predicted by theory and are typically inferred from so-called PDF fits in which parameterised distributions are fitted to experimental data within the framework of QCD. One commonly made assumption of these fits is that the amount of strange quarks and antiquarks to be found within the proton is less than that of the up and down antiquarks. This is expected because the mass of the strange quark is significantly larger than that of the up and down quarks, making it harder to produce. In Fig. 1, the struck quark in the proton (*q*) can be a strange quark, and hence this process gives us indirect information about the strange sea.

A team led by members of the DESY ATLAS group studied this while testing the effect of including ATLAS vector boson plus jet measurements from proton–proton collisions at a centre-of-mass energy of 8 TeV in these PDF fits for the first time [1]. The fits were performed using the open-source xFitter program, which allows scientists to study the structure of the proton and other complex particles.

To assess the effect of information from data with heavy bosons and jets, two fits were compared. The first used deep-inelastic scattering data from the HERA experiments [2] together with ATLAS measurements of Drell–Yan *W*- and *Z*-boson production, the second fit included *W* and *Z* plus jet measurements. Comparing the two fits demon-

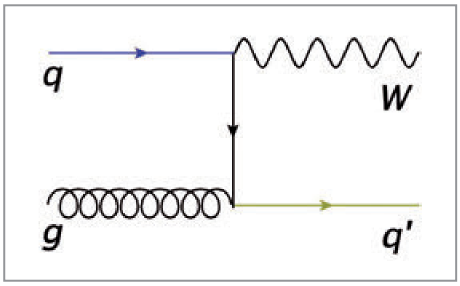

Figure 1

Example Feynman diagram showing the production of a *W* boson in association with a quark

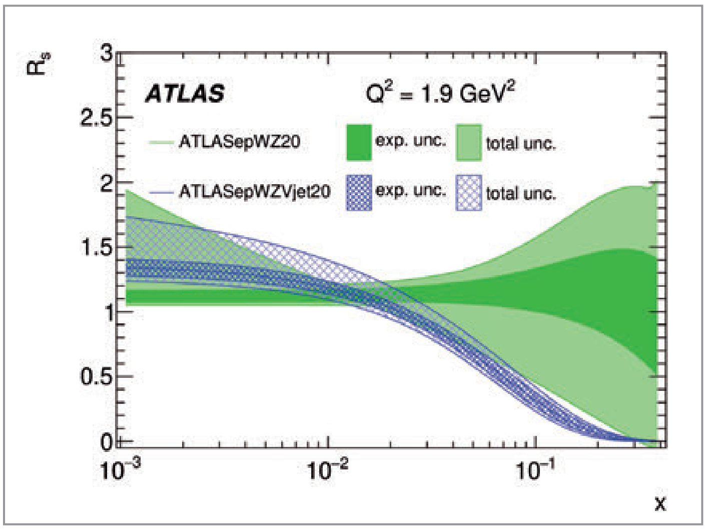

Figure 2

Strangeness suppression factor (R_S) extracted from the ATLAS PDF fit, including vector boson plus jet data (blue bands) compared to without (green bands). The bands show the size of the total fit uncertainties and the contribution to these from experimental uncertainties.

strated that the vector boson plus jet data mainly affected the fitted gluon, down-quark and strange-quark distributions.

One of the most striking results is shown in Fig. 2. This figure compares the strangeness suppression factor (R_S), which measures the ratio of the sum of the strange quarks and antiquarks to the sum of the anti-up and anti-down quarks as a function of x, the fraction of proton momentum carried by the quark. A value of 1 indicates no suppression, while values much less than 1 indicate that strange-quark generation is suppressed. Without including the vector boson data, the fitted ratio, shown as green bands, is compatible with no strangeness suppression. Including the vector boson plus jet data significantly reduces the uncertainties on this quantity and clearly shows suppression of the strange quark for higher values of x.

Measuring *W* plus charm production

It is also possible to measure the strange quark in the sea directly. The example Feynman diagram in Fig. 3 is very similar to Fig. 1. However, here, in the final state, a specific quark is identified: the charm (c) quark. In this example, this means that the strange quark took part in the initial phase of the collision. Thus, when one hadronic jet originates from a charm quark, it is possible to obtain direct information about the distribution of the strange quarks.

The production of a W boson plus charm quark was measured by the CMS collaboration using data from proton–proton collisions at the LHC at a centre-of-mass energy of 8 TeV [2]. Jets originating from charm quarks were selected by exploiting very specific behaviour of the charm-quark decays. The two characteristics used were the possibility of the charm quark to decay semi-leptonically, leading to well-identified muons within the jet, and the characteristic lifetime of the charm quark, which yields displaced vertices inside the jet.

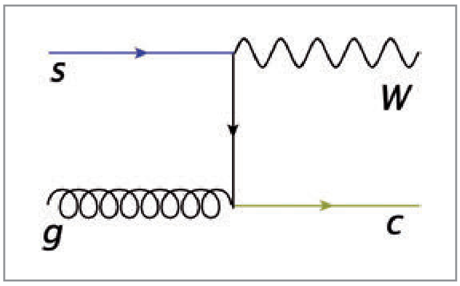

Figure 3
Example Feynman diagram showing the production of a *W* boson in association with a charm quark

Members of the DESY CMS group used xFitter to study how precisely we can measure the strange sea in two situations: with and without this W plus charm measurement. This is illustrated in Fig. 4, where the relative uncertainties of R_S with and without the W plus charm data are shown. As expected, it can clearly be seen that the measurement of the strange quark is more precise when the data including the direct information on the strange sea is used.

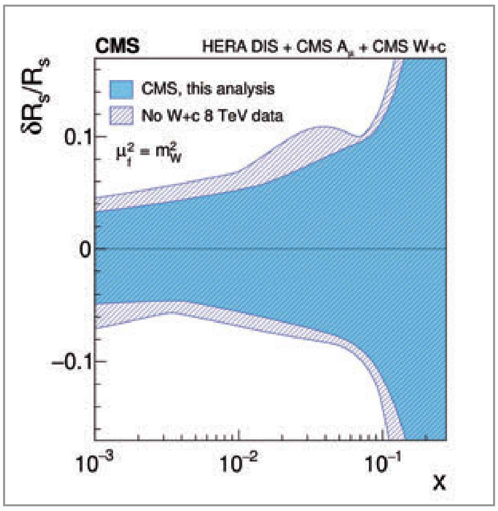

Figure 4
Effect of including the *W* plus charm data in a PDF fit on the uncertainty of the extracted R_S. The dark blue band shows a fit including the data, while the hashed blue band shows a fit without the data.

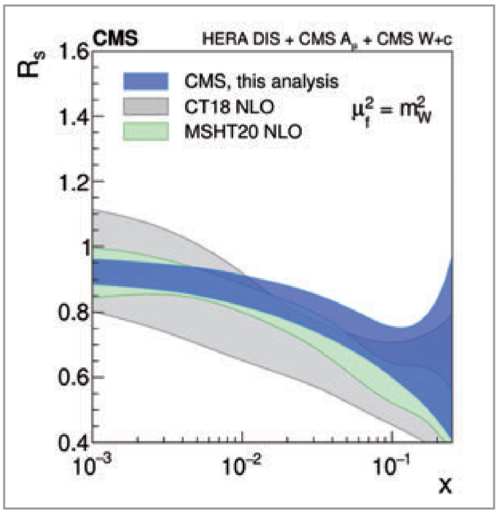

Figure 5
R_S distribution as a function of x extracted in the CMS study of *W* plus charm data

Figure 5 shows the shape of R_S together with the same variable predicted by different groups working on measuring the proton structure. Again R_S is smaller than unity and hints at the suppression of the strange quark compared to the other quarks in the proton sea. The bands in Fig. 2 and Fig. 5 show the uncertainties on the measurement of R_S; including more direct and indirect measurements of the strange sea would give us more precise information about R_S.

These studies of vector boson production in association with hadronic jets have shown the potential of such measurements to open a window onto the strange-quark content of the proton. The next step will be to see these data included in future global PDF fits that comprise other LHC physics processes in order to further enhance our understanding of the proton structure.

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References:

[1] ATLAS Collaboration, JHEP 223 (2021)
[2] H1 and ZEUS Collaborations, Eur. Phys. J. C 75, 580 (2015)
[3] CMS Collaboration, CMS-SMP-18-013, submitted to Eur. Phys. J. C (Dec. 2021)

The PUNCH4NFDI consortium

FAIR and sustainable data management for fundamental research in the German science system

In October 2021, the PUNCH4NFDI consortium [1] formally started its work in the framework of the German National Research Data Infrastructure (NFDI [2]), together with currently 18 other consortia from all fields of science. PUNCH4NFDI – with PUNCH standing for particles, universe, nuclei and hadrons – represents the efforts of the particle, astroparticle as well as hadron and nuclear physics communities plus the astrophysics and astronomy communities in Germany towards a sustainable data management according to the FAIR data principles (findability, accessibility, interoperability and reusability) [3]. From the funds that the Joint Science Conference (GWK) of the German federal government and states is allocating to the NFDI for the next decade, the consortium will receive more than 15 million euros in the next five years. DESY is acting as coordinator for the consortium.

Data in the PUNCH communities are very diverse – in terms of rate, format, size, level of abstraction and location. Over and over again, the PUNCH communities have been pioneers in providing data management solutions. Key examples are the Worldwide LHC Computing Grid (WLCG), which connects 170 computing centres distributed over the entire globe, facilitating access to the LHC data for a community of roughly 10 000 users, or the Virtual Observatory in astronomy, a forerunner in open scientific data.

With PUNCH4NFDI, we are addressing the next challenges in data management in our communities and beyond, such as the ever-increasing size of data volumes – reaching into the exabyte or even zettabyte regime with the HL-LHC or the upcoming Square Kilometre Array (SKA) observatory – or the increasing political and societal demands towards FAIR, open and sustainable research data. The work in the seven PUNCH4NFDI task areas focuses on the implementation of a science data platform that serves as a biotope for the entire life cycle of digital research products (DRPs). DRPs are research artefacts that encapsulate scientific data (or their location) at a usable abstraction level together with the relevant metadata descriptions and publications, the software required to act on the data and the interfaces to the relevant libraries, as well as storage and compute resources to execute workflows with the data.

Today, this science data platform and the DRPs are still a vision. But many necessary ingredients and concepts are already around. The main goal of PUNCH4NFDI is to make them a reality and provide their services to the around 9000 scientists in the research field in Germany – and beyond.

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References:

[1] The PUNCH4NFDI Consortium, https://www.punch4nfdi.de
[2] NFDI e.V., https://www.nfdi.de
[3] M.D. Wilkinson et al., Sci. Data. 3, 160018 (2016), doi: 10.1038/sdata.2016.18

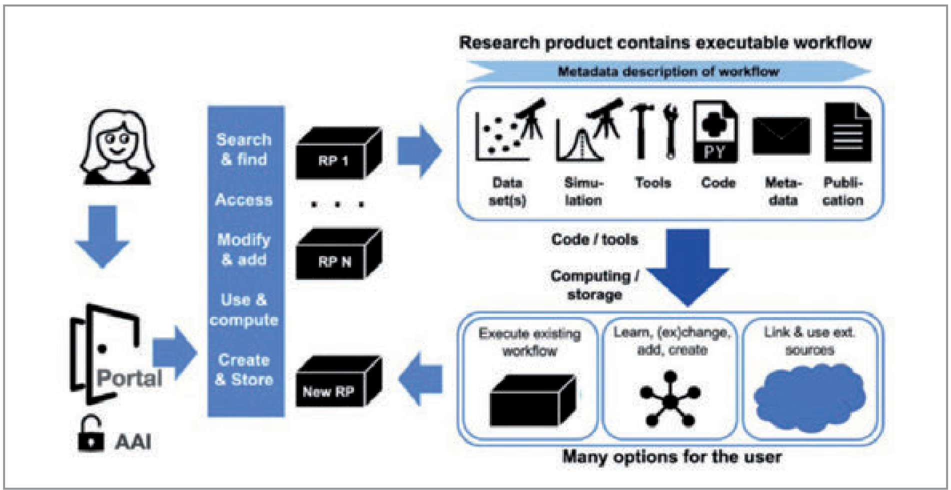

Figure 1
Visualisation of the PUNCH science data platform for digital research products (DRPs)

Communicating science and searching for new particles

Freya Blekman joins DESY through the Helmholtz Recruitment Initiative

In October 2021, particle physicist Freya Blekman joined DESY as a lead scientist. Blekman has earned an internationally renowned reputation in using top quarks to search for physics beyond the Standard Model. In addition, she is a well-known science communicator. Originally from the Netherlands, she comes to DESY via a joint appointment with Universität Hamburg within the Helmholtz Distinguished Professorship programme.

Yesterday's discovery is today's background and tool, and everyone's outreach

During her career, Freya Blekman has worked at the Dutch particle physics research centre NIKHEF, where she studied the then recently discovered top quark for her doctorate, using data from the D0 experiment at Fermilab. Since completing her PhD in 2005, she has been active in the CMS collaboration at the LHC at CERN, where she has held several leadership positions.

Blekman brings innovative science communication concepts to DESY. On Twitter, she is among the top ten most actively followed female physicists worldwide, and she is currently the first CMS physics communication officer, responsible for communication and outreach on the about 100 scientific papers per year produced by the more than 3000 members of the international CMS collaboration. In this position, Blekman has created a very successful effort of short articles aimed at the general public [1], and she has been involved in increasing the science communication efforts by the members of the CMS collaboration.

On the physics side, Blekman has been instrumental in organising the use of top quarks to search for new physics at the CMS experiment. The focus of Blekman's research in the CMS group at DESY will be on signatures that are only becoming available now, as the LHC data has become so large that the associated production of new undiscovered particles together with top quarks (not just decaying into top quarks) allows detailed and kinematic investigation. These kinds of signatures are partially still unexplored at the LHC, and they have links to models reaching from dark matter and new Higgs-like bosons to leptoquarks, the mysterious particles that are used as an explanation for recent deviations from the Standard Model prediction in the flavour sector.

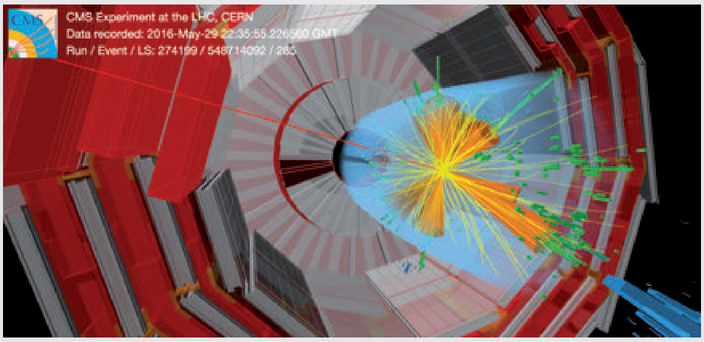

Figure 1

The production of four top quarks creates extremely busy collisions.

At DESY, Blekman will continue her important research on the production of four top quarks at the CMS experiment [2], which is expected to be one of the potential discoveries of the next LHC run. The isolation of LHC collisions containing four top quarks requires a very strong background rejection, for which the modern machine learning expertise already present at DESY will be instrumental. Blekman's interests are also linked to other DESY science, such as studies for potential future colliders, and have connections with the axion research programme.

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References:

[1] CMS Collaboration, https://cms.cern/tags/physics-briefing
[2] CMS Collaboration, JHEP 11, 082 (2019)

Development of the new ATLAS ITk strip detector

Busy times in the preproduction phase

The ATLAS collaboration is preparing for the necessary upgrades of the ATLAS detector to address the challenging conditions of the High-Luminosity LHC (HL-LHC) phase. The ATLAS group at DESY is heavily involved in the development, design, construction and installation of the new silicon tracking detector, called the ATLAS inner tracker (ITk). In 2021, the ITk project entered the phase of preproduction for various detector components. The DESY group, spanning both campuses in Hamburg and Zeuthen, played a leading role in the development of the manufacturing, tooling and quality control setups gearing towards the production phase of the experiment.

The new ATLAS tracker for the HL-LHC

With the high-luminosity upgrade of the LHC on the horizon at CERN, the ATLAS group at DESY has been developing a major part of the new tracking detectors for the ATLAS experiment. The ATLAS ITk will replace the current inner detector to cope with the challenging HL-LHC conditions. The DESY ATLAS group has been one of the leading forces of this project. Key contributions have been made to the design, production and construction of the strip end-cap detector, with its design shown in Fig. 1. The main building blocks of the end-cap are the petals (Fig. 1, right). A petal comprises a core structure with six different types of silicon strip modules glued on both sides and a data concentrator board at the end, called the end-of-substructure.

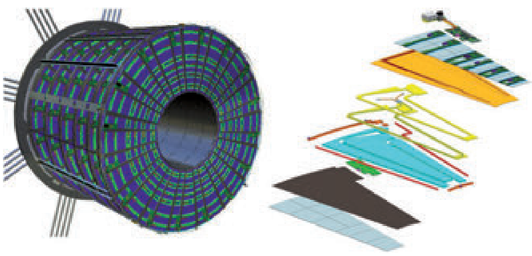

Figure 1
Conceptional design of one of the ATLAS ITk strip end-caps populated with petals

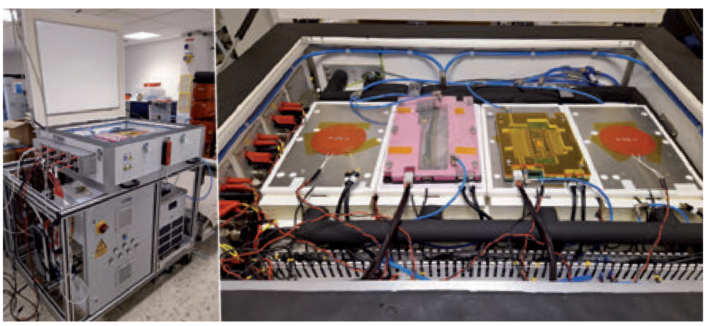

Figure 2
Module cold box for thermal cycling of assembled end-cap silicon modules

In 2021, despite the challenges brought on by the COVID-19 pandemic, the ongoing CERN review process (with several critical milestones) was successfully passed, and the project entered the phase of preproduction in most areas. Now, the lights are turning green towards the production of the ITk detector, both worldwide and locally at DESY.

Towards the production of ITk modules

An ITk strip module is composed of a ~10 x 10 cm^2 n-in-p silicon sensor with ~5000 strip implants. Thin flex boards loaded with readout chips and power/control board circuitry are glued onto it using an automatic glue-dispensing robot, and precision tool sets are used for the assembly. Novel tools for the assembly of one module type were designed and produced at DESY for the whole collaboration. Then, electrical connections are established between the components and the individual strips with about 6000 wire bonds.

After assembly, stringent quality control tests are applied to the modules, comprising measurements of geometric tolerances down to micrometres and electrical tests for functionality and performance. For the purpose of thermal cycling, where the electrical performance is tested at the highest and lowest expected operation temperatures, the DESY group designed, prototyped and tested an automated test setup, the module cold box, shown in Fig. 2. In total, 15 copies of this setup are being manufactured in the DESY workshops for distribution to the ITk strip community.

The preparations for the construction and testing of ITk strip modules are being finalised in the cleanrooms at DESY in Zeuthen and Hamburg, laying the groundwork for the production phase. This includes a collaboration-wide site qualification process and involves the successful

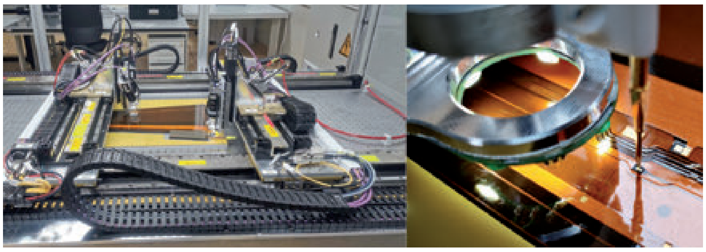

Figure 3

Robot for automatic electrical performance testing of petal bus tapes in the DAF

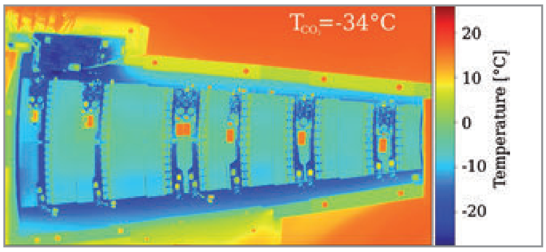

Figure 4

Thermal image of the powered-on electrical petal cooled with dual-phase CO_2

completion and documentation of the different module-building steps within the quality criteria.

Readiness of quality control tests for cores

The DESY ATLAS group also plays a leading role in the construction of the petal cores for the strip end-cap detector. Each core is made out of a lightweight "sandwich" composite structure using carbon fibre reinforced polymers (CFRP) with an embedded titanium cooling pipe. The structure gives mechanical support to the modules glued on both sides and provides cooling down to -35°C using dual-phase CO_2.

After the successful completion of the prototyping phase at DESY, the knowledge for series production is now being transferred to an industry partner in Spain. However, several components are still being manufactured, produced and quality-tested in the DESY mechanical and carbon fibre laboratories. Among these components are the face sheets at the core's top and bottom sides. They consist of three layers of CFRP pre-impregnated fibres ("prepreg"), co-cured in an autoclave along with the bus tape, a multilayer copper–polyamide structure with electrical power and data lines.

For the electrical performance tests of the bus tapes, an automatic testing robot, shown in Fig. 3, was developed and commissioned in the Detector Assembly Facility (DAF) at DESY. The electrical connectivity and the impedance of the copper lines of the bus tape are measured using two robotic arms equipped with needle probes. These tests are repeated at three different stages of the bus tape: in the bare state coming from industry, after co-curing to the face sheet at DESY and finally after assembly in the core. In this way, it is possible to monitor quality and detect possible defects at all stages. Various other quality control setups were developed and commissioned in the DESY laboratories to prepare for entering the preproduction phase for cores in 2022.

Cold testing of the first electrical petal

At the beginning of 2021, the first electrical petal populated on one side with fully functional silicon modules became available. It was built in a collaboration-wide effort with a large DESY contribution. The DESY ATLAS group performed the first successful measurement of the petal's electrical noise behaviour under realistic operational

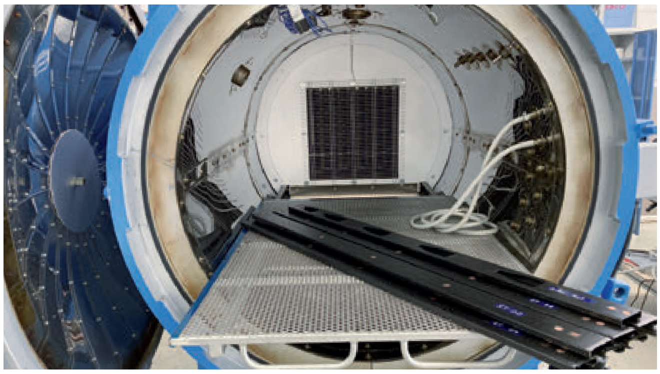

Figure 5

Carbon fibre service trays produced in the autoclave at the DESY carbon fibre lab

conditions, cooled down to -35°C with dual-phase CO_2, as illustrated in Fig. 4.

First deliverables for the ITk strip end-caps

The development of the procedure and tooling for the petal installation in the global end-cap structures as well as the design of tooling for the transport and integration of the end-cap at CERN are additional tasks of the ITk team at DESY. After successfully demonstrating the integration procedures and passing the corresponding ATLAS review in 2021, the team is now gearing up for the preparation of the final tool sets.

The first deliverables for the final detector were also produced at DESY in 2021. The service trays are 1.4 m long carbon fibre parts that belong to the mechanical structure of the end-cap. They hold the cooling pipes and guide the electrical power cables and optical fibres for data transmission off the detector. A total of 16 service trays, covering the full demands of the end-cap detector, were co-cured in 2021 in the autoclave of the DESY carbon fibre laboratory, as depicted in Fig. 5.

Thanks to a worldwide effort, in which DESY played a key role, the last few areas of the ITk project are entering the phase of preproduction, and the collaboration is steadily getting ready to tackle the challenges of production.

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Exploring the lifetime frontier

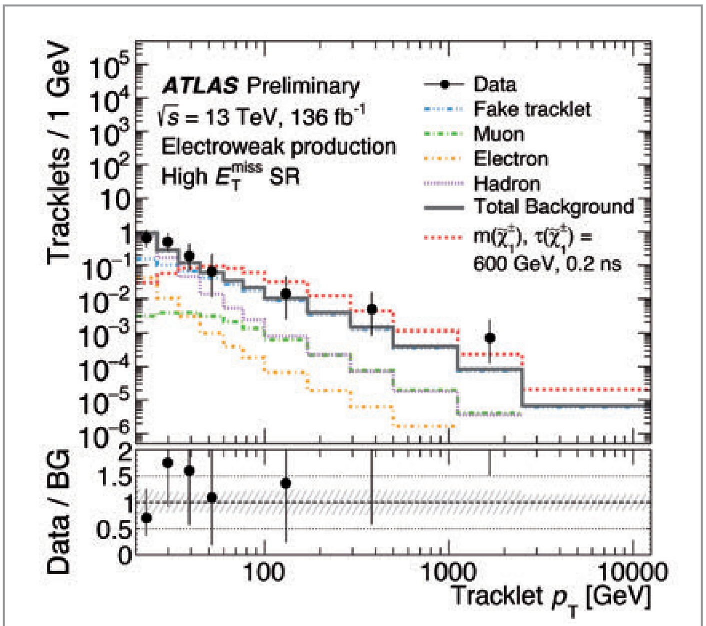
From 10 picoseconds to 10 years

The search for new phenomena in the proton–proton collisions delivered by the LHC is a key research topic of the ATLAS experiment. Scenarios predicting new particles with detectable lifetimes can provide answers to many fundamental open questions, but lead to significant experimental challenges. The ATLAS group at DESY has met these challenges head-on by developing dedicated techniques used in the analysis of the data collected between 2015 and 2018, thereby strongly extending the previous ATLAS reach across an extremely wide range of lifetimes for these hypothesised particles.

Introduction

Despite decades of predictive success, the Standard Model of particle physics can't answer several fundamental questions. What are the origin and nature of dark matter? What happened to antimatter in the visible universe? These are just examples of such open dilemmas. New theories must exist that can fully describe our universe and answer these questions, even though a definitive proof of their validity has yet to turn up.

The DESY ATLAS researchers are broadening their extensive search programme to look for new phenomena with unconventional signatures, such as long-lived particles.



These new particles could have lifetimes of 0.01 to 10 ns. For comparison, the Higgs boson has a lifetime of 10^{-13} ns. A theory that naturally motivates long-lived particles is supersymmetry (SUSY). SUSY predicts that there are "superpartner" particles corresponding to the particles of the Standard Model with different spin properties.

Searches for "disappearing" tracks

One particularly compelling scenario predicts new charged particles, called charginos, that are only a few hundred MeV heavier than a new neutral state, the neutralino, which acts as a dark-matter candidate. Because of the small phase space available for the decay, the heavier chargino acquires a non-negligible lifetime. This, in turn, means that the chargino flies partway through the ATLAS inner tracking detectors before decaying, and its short trajectory can be measured.

A search targeting these anomalous "disappearing" tracks was performed using the data collected with the ATLAS detector from 2015 to 2018 [1]. This search exploits new requirements on the quality of the reconstructed short tracks, referred to as tracklets, their reconstructed transverse momentum (shown in Fig. 1) and the presence of significant momentum imbalance to look for signs of new phenomena.

Figure 1

Tracklet p_T spectrum in signal-enriched regions. The backgrounds shown by the various lines are fit to observed data events in dedicated regions. An example of the expected signal prediction is overlaid in red. Taken from [1].

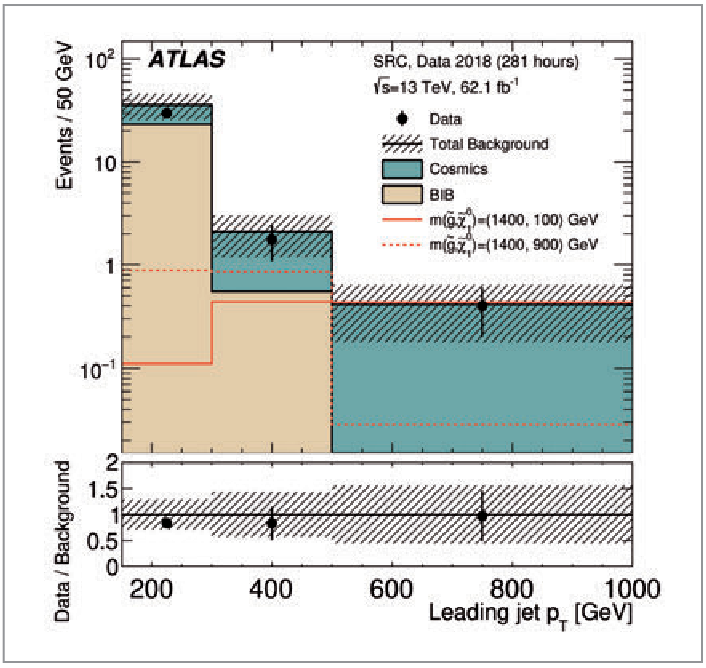


Figure 2

Observed and expected leading-jet p_T distribution in the 2018 data. Two example signal models are overlaid for reference. Taken from [2].

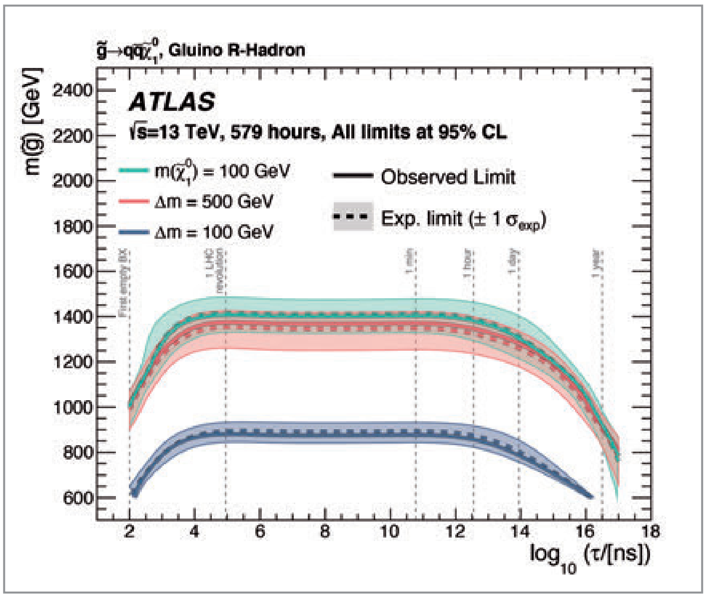


Figure 3

Expected (dashed lines) and observed (solid lines) exclusion limits at 95% confidence level as a function of gluino mass and lifetime τ. The different sets of colours represent the limits for different assumptions about the new particle masses considered in the model. Taken from [2].

The number of observed events with short tracks was found to be compatible with the predictions from background processes alone. These findings were used to rule out combinations of theory parameters incompatible with the observed data. In particular, the mass of the supersymmetric higgsino dark matter, which predicts a lifetime of a fraction of a nanosecond, was ruled out up to 210 GeV.

Searches for late decays

The exploration of unconventional experimental signatures led the DESY ATLAS group to perform a very special search [2]: Typically, physicists look for new particles produced in LHC collisions that immediately decay to known or invisible particles. This analysis, in contrast, looks for new long-lived particles that live long enough to travel large distances, well into the ATLAS detector itself.

If these new particles interact with matter, some fraction of them may lose their momentum and come to rest inside the densely instrumented regions of the detector. These particles may then decay at some later time. In order to reduce possible background effects, this search avoided collision data altogether: The analysis looked for energetic sprays of hadrons entering the calorimeter systems during time intervals in which no proton collisions are expected from the LHC.

The signal models inspiring this search come from "mini-split" supersymmetry models, where a large mass difference between supersymmetric particles induces a large lifetime for the gluino (the gluon's supersymmetric partner), which would be abundantly produced in the LHC collisions.

Searching for new phenomena outside of the LHC collisions means that the expected background contributions for this search originate from far outside the detector. These could come from energetic cosmic rays or from upstream interactions of the LHC beams that enter the signal selection, shown in Fig. 2. Reducing such backgrounds required dedicated mitigation techniques.

The observations were found to be in agreement with the expected backgrounds and showed no evidence of new phenomena. This allowed limits to be cast in terms of the gluino mass and lifetime, shown in Fig. 3. The results span an enormous range of particle lifetimes: from 100 ns to more than three years.

What comes next?

No evidence for the hypothesised long-lived particles was found, and so the DESY ATLAS group continues its hunt for new physics that may still be hiding in the data. There remain challenging "gaps" in the limits set on the masses and lifetimes of these new particles, and the search will be extended to new signatures and new areas of parameter space, employing new techniques to turn over every possible stone, until a hint of new physics is revealed.

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References:

[1] ATLAS Collaboration, ATLAS-CONF-2021-015
[2] ATLAS Collaboration, JHEP 07, 173 (2021)

Shining light on the Higgs boson

How does it couple to other Standard Model particles?

The Higgs boson is a central part of our understanding of the world of elementary particles. As such, it could be a window to what might exist beyond the Standard Model. Our understanding of how the Higgs boson interacts with other particles and whether this agrees with the predictions of the Standard Model is obtained from studies of its production and decay. Given that its interaction with lighter particles is weak, indirect measurements can provide valuable information to supplement direct measurements. This article highlights some of the results recently obtained with the help of the DESY ATLAS group and explains how these results help shine light on the Higgs boson.

Higgs-boson couplings

The most direct way to probe the coupling of various particles to the Higgs boson is to measure the rate at which a Higgs boson is produced via the interaction of those particles and the rate at which it decays into them. To obtain a more complete picture and disentangle the production and decay contributions in total-rate measurements, it is particularly interesting to perform a statistical combination of all available measurements. Such a combination was performed in 2021 [1], culminating in the most detailed and precise picture of Higgs-boson couplings so far. As illustrated in Fig. 1, this picture shows excellent agreement with the Standard Model (SM) prediction that the strength of the couplings increases with the particle's mass [1].

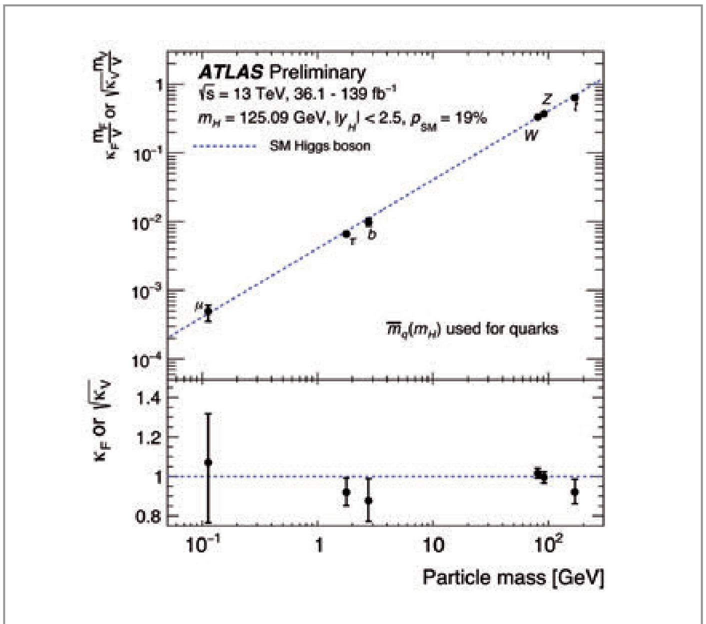

Figure 1

Couplings of known particles to the Higgs boson, parameterised using κ coupling modifiers, as a function of the particle's mass. The measurements are in agreement with the behaviour predicted by the SM (blue dashed line).

What other measurements can tell us

Precision measurements of the Higgs boson in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ'$ channels have also been performed. In these channels, it is possible to not only measure the rates of Higgs production and decay, but also study kinematic distributions.

As illustrated in Fig. 1, Higgs-boson couplings to lighter SM particles are weaker, making it more difficult to measure them. However, the Higgs-boson kinematics can provide additional information. The shape of the Higgs-boson transverse-momentum distribution in particular is sensitive to how the Higgs boson interacts with other particles. This characteristic was exploited to set constraints on the strengths of the Higgs-boson couplings to charm and bottom quarks [2].

The results obtained in the $H \rightarrow \gamma\gamma$ and $H \rightarrow ZZ'$ channels as well as a combined result, which complement those from direct measurements and provide additional constraints to the strength of the interactions, also show good agreement with the SM, prompting the ATLAS collaboration to continue looking for new ways to push the limits of our understanding of the world of elementary particles.

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References:

[1] ATLAS-CONF-2021-053
[2] ATLAS-CONF-2022-002

Searches for dark matter with ATLAS

Looking for invisible particles with the LHC

Astrophysical observations indicate that only about 26% of the universe's matter content consists of known types of matter. The rest is composed of something that has mass but doesn't interact with photons – called dark matter – whose nature remains one of the major open questions in particle physics and cosmology today. Among many possible explanations, theories predicting the existence of a new particle in the TeV range are particularly interesting and can be probed by the ATLAS and CMS experiments at the LHC. In collaboration with institutes all over the globe, DESY is strongly involved in investigating the particle nature of dark matter.

On top of dark matter and Higgs bosons

Most elementary particles acquire their mass by interacting with the Higgs field. A particularly interesting class of theoretical models describes how dark-matter particles could be created at the LHC by postulating the existence of additional heavy Higgs bosons. In the 2HDM+a model [1], these particles interact primarily with heavy particles, resulting in enhanced interactions with top quarks. Consequently, the model can be tested with an unprecedented sensitivity by combining information from searches that probe dark matter with Standard Model Higgs bosons and top quarks.

The ATLAS collaboration recently published a search for dark-matter particles produced in association with Higgs bosons decaying to bottom quarks, using the full LHC Run-2 data set collected by ATLAS [2]. For the first time, signatures that correspond to the associated production of Higgs bosons with bottom quarks were investigated, thereby improving the reach towards a wider class of dark-matter models.

Other recently published results [3] investigate for the first time within ATLAS signatures involving a single top quark and dark matter using the 2HDM+a model. These results look at final states with either one single top or a single top and a *W*, focusing on final states with one or two charged leptons and neutrinos.

Combining forces towards discovery

Together, the null results of these searches constrain the still viable parameters of the model. Figure 1 shows the configurations of model parameters that are ruled out at 95% confidence level: Only the remaining white space in the plot corresponds to predictions that are not in conflict with observations. Ultimately, these findings suggest that there is still a lot of unexplored territory where dark matter could be found and that new ideas could give us a hint of its existence and nature.

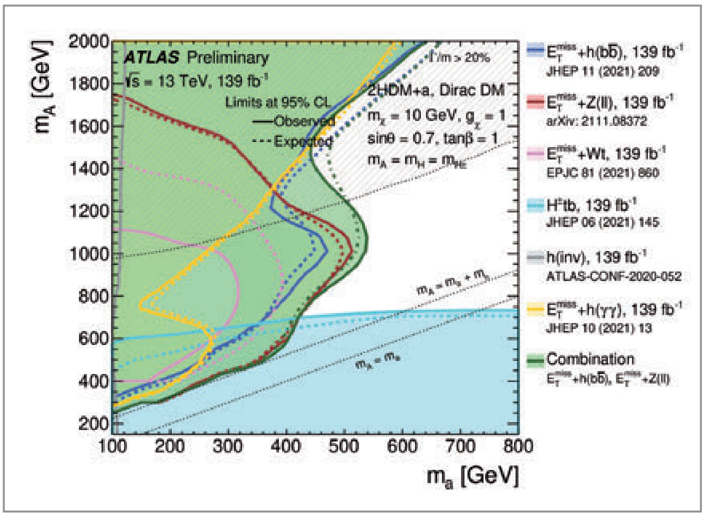

Figure 1

Exclusion limits [4] at 95% confidence level in the (m_A - m_a) plane defined assuming a 2HDM+a model [1] of dark-matter (DM) production at ATLAS. Observed (solid) and expected (dashed) lines are shown for each individual search, including Higgs+DM and *tW*+DM final states, as is the combined exclusion limit (green lines and filled area). A mass of 10 GeV is assumed for the DM particle.

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References:

[1] LHC Dark Matter Working Group, Phys. Dark Univ. 27, 100351 (2020)

[2] ATLAS Collaboration, JHEP 11, 209 (2021)

[3] ATLAS Collaboration, Eur. Phys. J. C 81, 860 (2021)

[4] ATLAS Collaboration, ATL-PHYS-PUB-2021-045

The future is monolithic

Thin and fast silicon detectors for beam telescopes and next-generation collider experiments

Silicon sensors play an important role in tracking detectors and are also used in the ATLAS and CMS detector upgrades driven by DESY. However, classical hybrid sensors cannot cope with the requirements at next-generation experiments. DESY has therefore formed a strong team with members from many DESY particle physics groups united in a project called TANGERINE, funded through the Helmholtz Innovation Pool. In cooperation with partners from other institutes throughout Europe, the project team wants to pioneer monolithic active pixel sensors in a new technology with small feature size. As a first application of the technology, the TANGERINE project aims to develop a chip suited for upgrading the beam telescopes at the DESY II Test Beam Facility. In parallel, DESY is working intensively on upgrading the existing telescopes.

Silicon-based tracking detectors

For a particle to be detected, it has to generate a signal in a detector – the larger the signal, the better the detection. On the other hand, signal-generating interactions change the properties of the particle, such as kinetic energy or direction of movement. Therefore, sensors must always be developed in such a way that they need only minimal interaction to ensure reliable particle detection.

In the past decades, hybrid silicon pixel sensors have been the workhorses for most large tracking detectors in particle physics. However, they are reaching their limits in terms of complexity and cost, require a relatively high material thickness and cannot cope with the requirements placed on next-generation sensors. Hence, new options are being investigated. One promising technology is a so-called monolithic active pixel sensor, where the readout electronics and the sensitive volume are placed in a single piece of silicon. Thin active layers of only 10–50 µm can be realised, allowing for ultralow-material detectors.

Figure 1

Prototype sensor response to an iron-55 X-ray source

DESY explores the potential of these technologies in two projects: TANGERINE studies a new 65 nm CMOS imaging technology for future detectors. TelePix is an upgrade for the DESY II beam telescopes, which should be completed in 2022.

TANGERINE: Towards next-generation silicon detectors

The TANGERINE project is a Helmholtz Innovation Pool initiative exploring new technologies and ideas in cooperation with KIT in Karlsruhe and GSI in Darmstadt, Germany. The DESY team is investigating a new 65 nm CMOS imaging sensor process, which only recently became available for science applications, in a shared effort of several groups from the DESY particle physics division (ATLAS, CMS, FE and FTX). This completely new CMOS process comes with several challenges, but also offers many opportunities: It provides the chance to work on a process where the team can help to build a solid knowledge base for the coming years and directly influence ongoing process developments.

The FE group designed a first sensor prototype, which was then characterised in laboratory and test beam measurements. Figure 1 shows the sensor response to an iron-55 X-ray source, which is expected to provide a larger signal than a minimum-ionising particle would. The sensor response demonstrated that the electronics implemented in the pixel cells are fully functional and perform as simu-

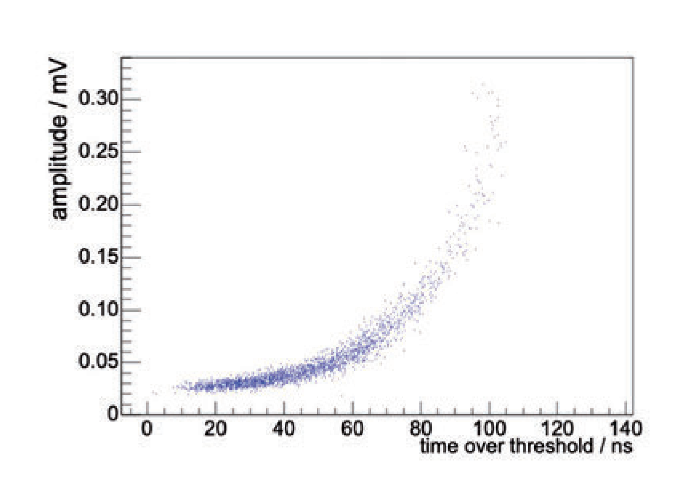

Figure 2

Relation between pulse amplitude and pulse length, measured at MAMI

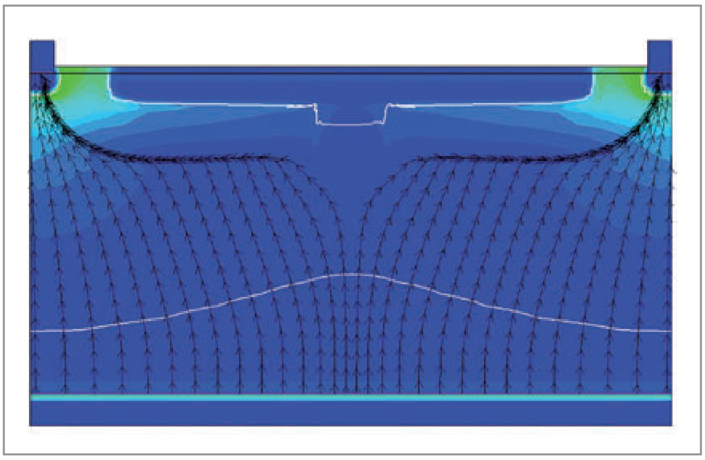

Figure 3

Simulation of the electric field strength in a silicon sensor. The colours indicate the electric field magnitude, the lines the path that an electron would take.

lations predict. Additionally, the team measured the sensor response to electrons from the DESY II test beam [1] and from the MAMI test beam at the University of Mainz in Germany as well as to pions from the SPS accelerator at CERN. The correlation between signal duration and amplitude is shown in Fig. 2 for data taken at MAMI.

Simulations to understand and optimise sensor charge collection properties

Since the design and especially the submission of sensor prototypes are expensive, the TANGERINE team is performing intensive simulation studies to predict the performance of certain changes to the sensor geometry. Finite element simulations [2] are used to generate detailed electrostatic potentials, which define the electric field lines along which charges within a sensor move. In thin monolithic sensors, these fields are highly non-linear. An example simulation result is shown in Fig. 3. The colours in the figure indicate the electric field strength and the black lines the path that an electron in the sensor would travel along in the ideal case.

Besides the directed movement of charges along electric field lines, a thermally induced random walk has to be added to accurately describe the motion of charges in silicon, as well as so-called Landau fluctuations in the generation of charge carriers as a particle interacts with the sensor. Since these are random distributions, simulations with high statistics are required for accurate results. The finite element simulations are computationally expensive, however, so a fast Monte Carlo simulation framework called Allpix^2 [3] is used at this stage.

Allpix^2 can load the fields generated by the finite element simulations and perform high-statistics Monte Carlo studies

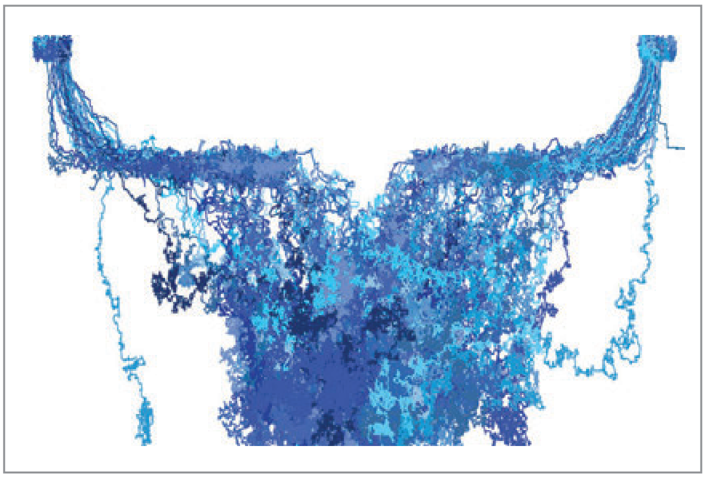

Figure 4

Electron paths in a sensor simulated using Allpix^2. The electrons follow the field lines shown in Fig. 3, but also have a random-walk component.

of charge deposition, propagation and collection, as well as signal digitisation (thus also including an approximation of the readout electronics in the simulations). By running the simulations for a large number of different events where particles hit the sensor, the stochastic effects inherent in the physical processes can be taken into account correctly. Figure 4 shows the electron paths in a sensor simulated with Allpix^2 for a single event. Comparing this to Fig. 3, it can be seen that the electrons follow the field lines, but also have a random-motion component added.

From the high-statistics simulations, all relevant performance parameters, such as sensor efficiency and spatial resolution, can be extracted as a function of the detection threshold. The performance of different sensor geometries and setups can then be compared by looking at the final performance observables. The combination of detailed finite element simulations and high-statistics Monte Carlo simulations is thus a powerful tool to gain insight into sensor behaviour.

Examples of both efficiency and resolution for different detection thresholds for a simulated sensor geometry are

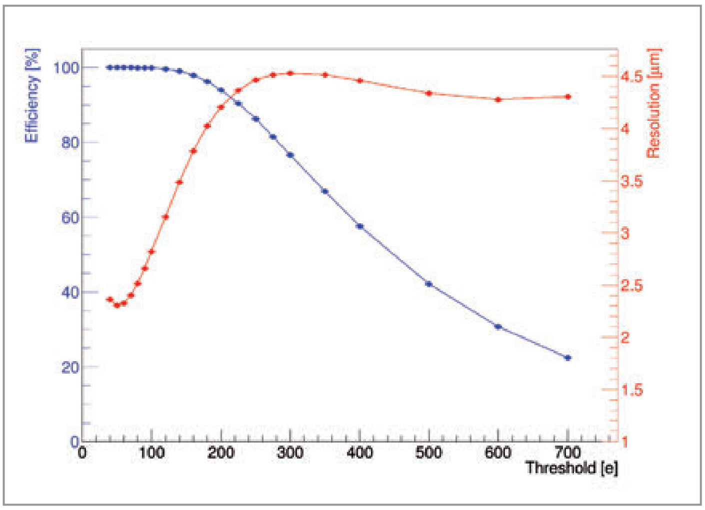

Figure 5

Efficiency and resolution results of a high-statistics simulation of a silicon pixel sensor for different detection thresholds

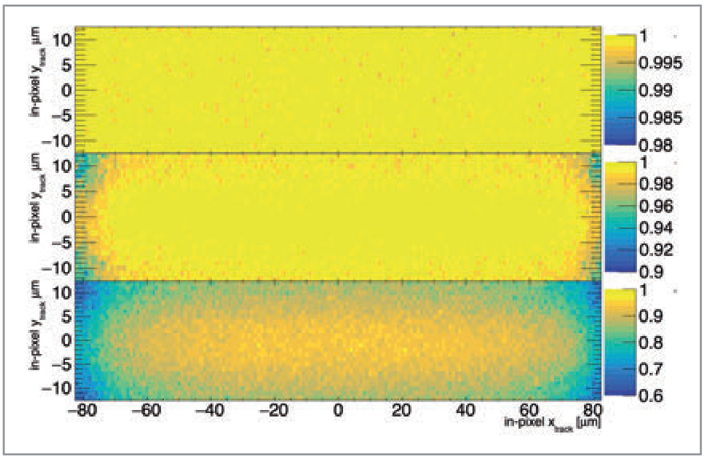

Figure 6

Efficiencies for three different detection thresholds (from top to bottom: 108 mV, 249 mV and 334 mV). Note the change in the colour scale.

displayed in Fig. 5. The blue curve and the left *y*-axis show the efficiency in percent, while the red curve and the right *y*-axis indicate the resolution in micrometres. The signal detection threshold is shown on the *x*-axis. Since the number of events in the simulations is so high, the statistical errors on the results are very small. It can be seen that high efficiencies and excellent resolution both require a low detection threshold and thus pose strict requirements on the allowed noise levels. This information is shared with the electronics engineers, who in turn develop the circuitry to optimise the front-end for the available signal.

HV-CMOS upgrades to the test beam facility

To study new sensors in test beam campaigns (as close as possible to a real experiment), reference systems are needed to determine the temporal and spatial properties of incoming particles. A beam telescope is essentially a three-dimensional camera for particles. The current telescopes at the DESY II Test Beam Facility have insufficient temporal precision, however. While TANGERINE is aiming to develop a sensor for a new beam telescope, the DESY II test beam team is upgrading the existing telescopes.

Together with partners at KIT and Heidelberg University as well as with substantial funding from the cluster of excellence Quantum Universe, the team has realised a new high-voltage (HV) CMOS [4] timing layer for the beam telescopes: the TelePix, which can be used to trigger the readout of the telescope and provide a precise time stamp on each incoming particle. A smaller prototype was studied in the test beam in 2021 and showed excellent performance.

Efficiencies for three different thresholds are shown in Fig. 6, mapped to a single pixel. For low thresholds, the efficiency is 100%. Only with increasing thresholds can particles no longer be reliably detected, first in the corners, then at higher thresholds also along the edges and finally in the centre.

Additionally, the time resolution of the sensor is crucial to time-tag the tracks that belong to each trigger issued for events with multiple particles. The measured time resolution of the TelePix is defined as the Gaussian sigma between the hit time stamp and the time reference scintillator. Only hits that can be assigned to a particle are taken into account. Figure 7 shows this for a low threshold of 108 mV, with a remarkable time resolution of approximately 3.5 ns. (This corresponds to measuring the distance from the Earth to the moon with a precision of 10 cm).

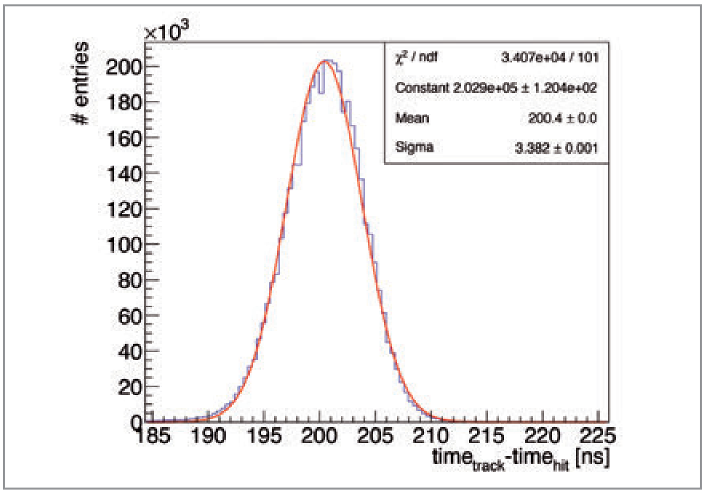

Figure 7

Time resolution of the TelePix at a detection threshold of 108 mV

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References:

[1] R. Diener et al., Nucl. Instrum. Meth. A 922, 265–286 (2019)
[2] TCAD, https://www.synopsys.com/silicon/tcad.html
[3] S. Spannagel et al., Nucl. Instrum. Meth. A 901, 164–172 (2018)
[4] I. Peric et al., IEEE J. Solid-State Circuits 56, 2488–2502 (2021)

Glimpse of rare *B* decay with two invisible neutrinos

First Belle II *B* physics paper already sets competitive limit

Researchers from DESY working on the Belle II experiment at the SuperKEKB collider at KEK in Japan have published the first Belle II paper with all subdetectors installed since the beginning of data taking. They studied the decay of *B* mesons, produced in pairs in electron–positron collisions at Belle II, into a kaon and a pair of neutrinos – a rare but highly interesting decay involving a beauty (*b*) to strange (*s*) quark transition.

Novel reconstruction approach

The DESY researchers performed the search for $B^+ \to K^+ \nu\bar{\nu}$ decays with the first 63 fb^{-1} of the Belle II data [1]. At first glance, searching for this decay with such a small data set may seem to be a step too far given that only one out of about 200 000 *B* mesons is expected to decay like this and that the decay produces two neutrinos, which do not leave any signature in the detector. But the novel reconstruction approach, the good performance of the Belle II detector and the use of advanced machine learning algorithms allowed the DESY scientists to set a competitive limit even though earlier experiments had roughly ten times more data available.

Significantly higher signal efficiency than that of previous searches was achieved by implementing a novel reconstruction approach. In this case, the track with the highest transverse momentum consistent with the kaon hypothesis was reconstructed as a signal candidate, followed by basic reconstruction of other tracks and energy deposits from the decay of the other *B* meson in the event. Resulting variables, such as signal kinematics, event topology and vertexing properties, were then used as input for machine learning algorithms to discriminate between signal and backgrounds. The innermost pixel vertex detector (PXD), whose commissioning and operation is led by DESY, proved to be especially powerful in suppressing backgrounds that do not originate from *B*-meson decays.

As no significant signal was observed in the data, a competitive limit of 4.1 x 10^{-5} was set on the branching fraction of $B^+ \to K^+ \nu\bar{\nu}$. As shown in Fig. 1, the measured branching fraction of $B^+ \to K^+ \nu\bar{\nu}$ was found to be in agreement with the Standard Model (SM) prediction and with previous measurements. Even if, at the moment, the measurement agrees well with the SM, the picture may change with more data, given that $B^+ \to K^+ \nu\bar{\nu}$ is a strong contender for finding new physics. It is, after all, a $b \to s$ transition, where several anomalies with hints at violation of lepton flavour universality have been reported [2].

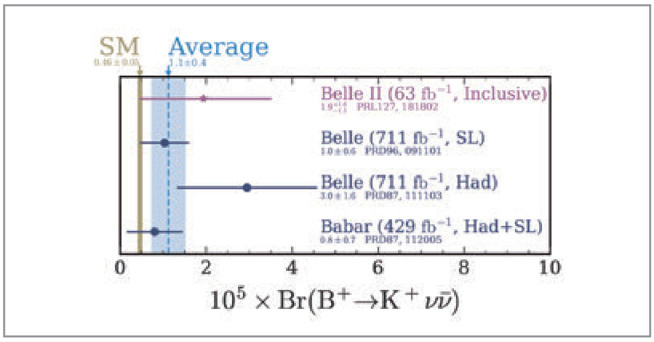

Figure 1

Measured branching fraction of $B^+ \to K^+ \nu\bar{\nu}$ with inclusive reconstruction (purple) compared with other measurements. SL and Had (blue) denote reconstruction methods that rely on the reconstruction of the *B*-meson signal and in addition on the explicit reconstruction of the other *B* meson in its semi-leptonic and/or hadronic decay chains.

Figure 1 also shows that the novel reconstruction approach proves to be most performant when scaled to equal luminosity. Hence, as Belle II accumulates more data, the new approach will not only allow the SM prediction for this particular decay to be tested on a shorter time scale than originally anticipated, but it can also be applied to other interesting decay channels at Belle II with invisible particles.

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References:

[1] Belle II Collaboration, Phys. Rev. Lett. 127, 181802 (2021)

[2] LHCb Collaboration, Nat. Phys. 18, 277–282 (2022)

Striving for ever better performance

SuperKEKB and Belle II face new challenges in uncharted territory

Accelerator physicists at the SuperKEKB electron–positron collider at KEK in Japan are continuously working on improving their understanding of this complex facility, with the goal to gradually approach the very ambitious design luminosity. This means constantly trying to find the optimal balance between exploring new phase space regions in terms of machine parameters and providing stable running conditions for efficient data taking of the Belle II experiment. This approach resulted in very successful data-taking periods in 2021 and enabled the Belle II collaboration to collect a total integrated luminosity of 268 fb^{-1}, while the accelerator experts were able to further increase the peak luminosity to the new record value of 3.8 x 10^{34} $cm^{-2}s^{-1}$. Although the anticipated total Belle II data set of 50 ab^{-1} is still a long way off, a number of highly relevant analyses can already be carried out with the existing data.

SuperKEKB operation

The development of the luminosity recorded by Belle II since the beginning of the Phase 3 data taking in 2019 is shown in Fig. 1. A total of almost 268 fb^{-1} of physics data was recorded by the end of 2021.

Although this value falls somewhat short of earlier expectations, important goals were achieved in the data-taking period after the summer break in 2021. The successful operation of SuperKEKB at centre-of-mass energies slightly above the nominal energy of the $\Upsilon(4S)$ meson enables the investigation of hitherto poorly understood phenomena in this energy range. Furthermore, an important milestone on the way to higher luminosities was the operation with beam currents above 1 A. Thanks to a series of improvements implemented during the summer shutdown of SuperKEKB, this important goal could be achieved in the Low Energy Ring (LER) in the second half of December. Thanks to the increased beam currents, a new record value for the instantaneous luminosity of 3.8 x 10^{34} $cm^{-2}s^{-1}$ could also be achieved.

In former run periods, uncontrolled beam losses had caused very high dose rates in the interaction region on several occasions, which resulted in massive quenches of the superconducting final focus magnets and in local damage to readout channels of the pixel vertex detector (PXD). Fortunately, after replacing the damaged collimators during the summer shutdown, no further "catastrophic" beam loss events occurred despite the gradual increase in beam currents. However, understanding the origin of these beam losses and finding means to avoid them in the future remains one of the major challenges for future data-taking periods.

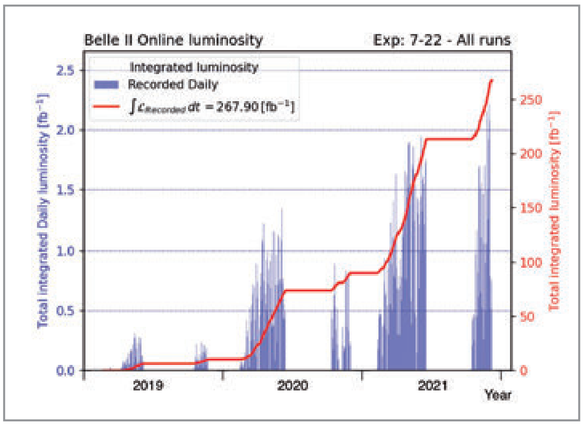

Figure 1

Development of daily (blue) and integrated (red) luminosity recorded by Belle II from 2019 to 2021

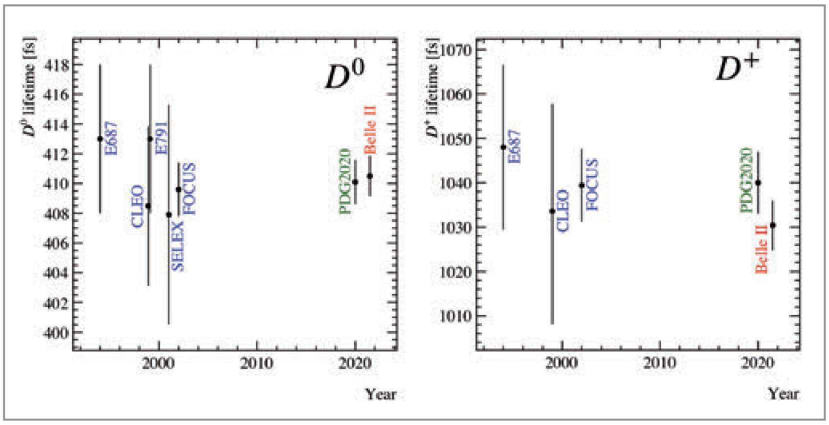

Figure 2

Result of the first Belle II measurement of D^0 and D^+ lifetimes compared with previous measurements. The Belle II result improves on the previous world average.

Moreover, there are still a number of machine-physical limitations in SuperKEKB that must be overcome to achieve the final luminosity goal of 6 x 10^{35} $cm^{-2}s^{-1}$. For this reason, KEK established an international task force of accelerator experts in summer 2021 to help work out solutions to these problems.

PXD status and PXD2 production

The automation of PXD operation has progressed further and gained in importance, especially in view of the ongoing restrictions on the availability of on-site PXD experts due to the coronavirus pandemic.

The measurement of the lifetime of D^0 and D^+ mesons is the subject of a recent Belle II publication [1]. As shown in Fig. 2, the precision of the results exceeds that of previous world averages and impressively demonstrates the outstanding performance of the Belle II PXD in combination with the small beam tube diameter, which is reduced compared to the former Belle experiment at the predecessor collider KEKB. In addition, the measurement is proof of the already very advanced understanding of the tracking system and in particular the alignment of the vertex detectors (PXD and SVD) and the central drift chamber (CDC), which is based on the Millepede II software developed in Hamburg.

Once SuperKEKB will reach even higher luminosities, the hit density in the PXD will increase accordingly. To avoid degrading the vertex resolution due to the currently missing second PXD layer, replacing the detector with the fully instrumented PXD2, which is currently under construction at various laboratories in Germany, is one of the top priorities of Belle II in the next long shutdown (LS1). Production of the PXD2 modules in Munich (at HLL and MPP) is making very good progress despite some technical delays. The newly manufactured modules are then distributed to several institutes (Univ. Bonn, DESY, Univ. Göttingen, MPP), where they are characterised and optimised in detail before they are combined to so-called PXD ladders at MPP.

Figure 3 (top) shows the first fully assembled “hot” PXD2 half-shell, which will be fully characterised and optimised using a radioactive ^{90}Sr source at the newly constructed, dedicated test stand at DESY (Fig. 3, bottom) in spring 2022. After completion of the construction of the second half-shell at MPP in early summer 2022, it will undergo the same procedure at DESY over the summer.

The schedule for the installation of the PXD2 in LS1 recently had to be modified. The main reason for this change, in addition to delays in the completion of the new central beam pipe at KEK, is the dramatically increased electricity cost in Japan, which will reduce the operation time of the accelerator in 2022 by about a factor of 2 due to budget constraints. LS1 is now scheduled from July 2022 to October 2023.

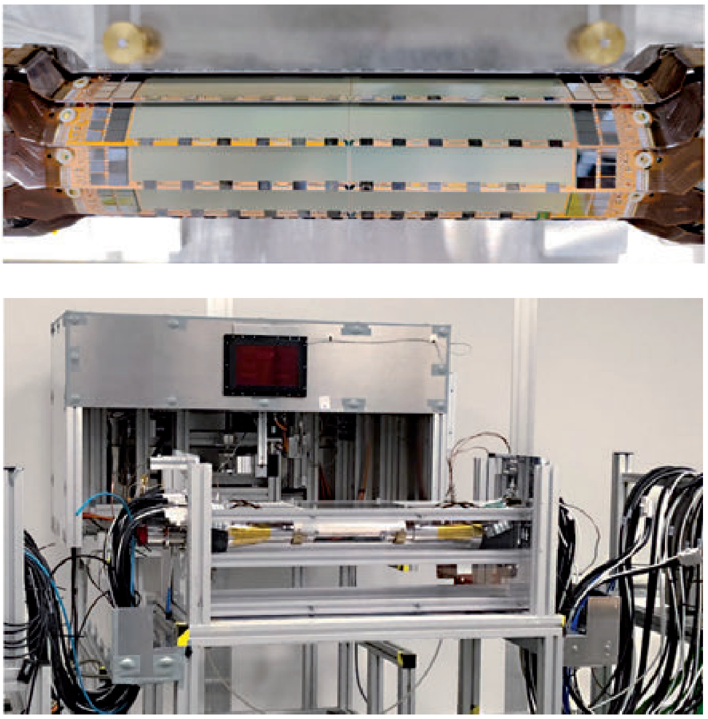

Figure 3

First fully instrumented half-shell of the newly constructed PXD2 (top). After mounting the detector on a dummy beam pipe, it will be subjected to a thorough test procedure using a special source setup installed in the cleanroom of the Helmholtz detector laboratory in the HERA West hall at DESY (bottom).

Physics analyses

As described in more detail in a separate article in this annual report, the first Belle II publication in the area of *B* physics is a search for the rare decay $B^+ \to K^+ \nu\bar{\nu}$ [2]. This decay is particularly relevant in the context of mounting evidence from various experiments for a possible violation of lepton flavour universality. This analysis was fully developed by members of the DESY group. In addition, the group is intensively pursuing analyses involving other $b \to s$ and $b \to c$ transitions that are also sensitive to the presence of physics beyond the Standard Model.

An electron–positron collider such as SuperKEKB does not only produce vast amounts of *B*- and anti-*B*-meson pairs but is at the same time an abundant source of $\tau^+\tau^-$ pairs. The use of this large-statistics τ sample, which takes advantage of the excellent Belle II detector performance, is being exploited for precision measurements of particle properties, such as the τ mass or lifetime, as well as for the search for τ decays into a lepton and an invisible particle and for tests of lepton flavour universality in τ decays. Several of these DESY analyses are aimed for publication in the near future.

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References:

[1] Belle II Collaboration, Phys. Rev. Lett. 127, 211801 (2021)
[2] Belle II Collaboration, Phys. Rev. Lett. 127, 181802 (2021)

ADVANCEs with plasma

Cutting-edge plasma source development at DESY's ADVANCE lab

Plasma wakefield accelerators have the potential to shrink the size of particle accelerators thanks to their ability to sustain ultrahigh accelerating-field gradients, orders of magnitude higher than their conventional counterparts. A critical component of such accelerators is the plasma source itself, in which plasmas capable of supporting GV/m accelerating gradients are generated. To accelerate particle bunches to high energies without loss of beam quality, precise tailoring of the spatial and temporal plasma profile is required. The ADVANCE (ATHENA plasma DeVelopment ANd Characterisation Experiment) laboratory is being commissioned to drive the development and characterisation of discharge-based plasma sources for multiple applications at DESY. Such sources are expected to have direct application to high-repetition-rate plasma-based particle physics facilities of the future.

Why plasma wakefield accelerators?

Plasma wakefield accelerators could hold the key to revolutionising future particle accelerator facilities by significantly shrinking their footprint through the use of GV/m plasma-based accelerating stages [1–3]. Imagine if hundreds of metres of radio frequency accelerating structures could be reduced to a few metres of plasma devices? The concept of accelerating and focusing charged particles using centimetre-scale plasma devices has already been demonstrated at the 1 to 10 Hz level [4–6], but this must be catapulted into the multi-kHz continuous-wave or MHz burst regime in order to compete with the integrated-luminosity demands of modern experiments.

An essential component: the discharge plasma source

All plasma accelerator experiments at DESY require plasma sources with well-tuned and extensively characterised plasma profiles. Many of these experiments – such as FLASHForward, KALDERA, PLASMEDX, PIP4 and the cSTART plasma injector – either require or could benefit from plasmas that are generated by ionising a neutral gas with an electric discharge.

In a typical discharge-ionised plasma source [7–9], a neutral gas confined within a solid structure is ionised by a high-voltage current pulse. Control of the spatial and temporal plasma profile can be realised by careful design of the structure confining the material, tuning of the current pulse properties and detailed knowledge of the evolution of the plasma. In this mode, discharge plasma sources have several important applications in accelerator and photon science:

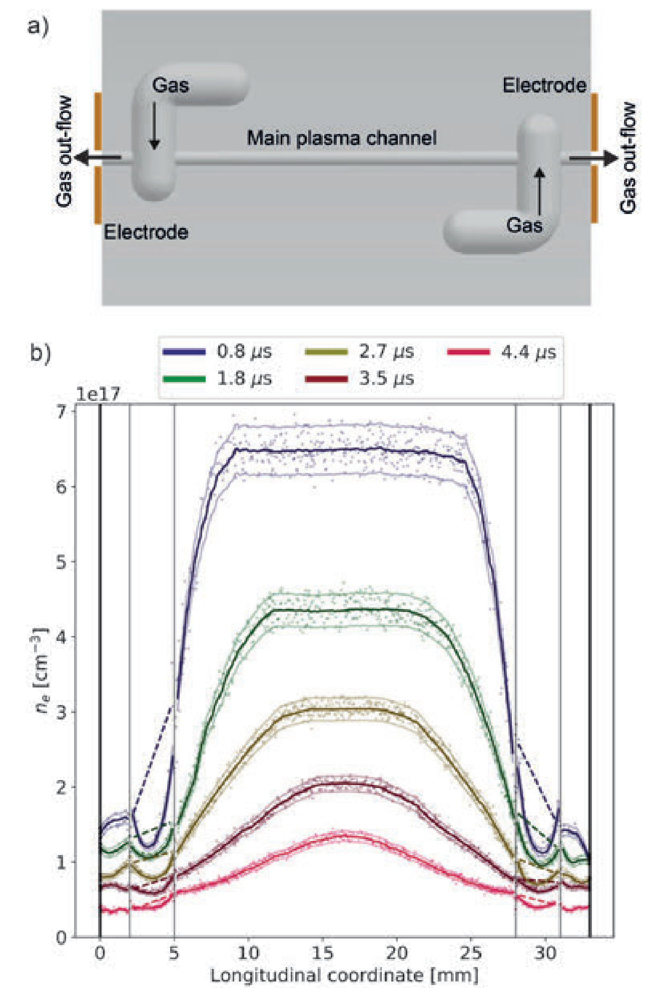

Figure 1

a) Schematic of an accelerating-stage plasma source. b) Spatially and temporally resolved plasma density profile along the beam axis.

- High-gradient accelerating structures for plasma wakefield acceleration
- Guiding structures for lasers and other electromagnetic radiation over multiple Rayleigh lengths
- Active plasma lenses (APLs) for radially uniform focusing of charged-particle beams

Figure 1a) shows the geometry of a plasma source used as an accelerating stage at the beam-driven plasma wakefield accelerator experiment FLASHForward at DESY [10]. Figure 1b) shows the measured plasma density profile along the longitudinal axis of the electron beam in such a cell. The non-uniform nature of the profile demonstrates that a detailed knowledge of the plasma profile is crucial in order to understand the nuanced acceleration of particle beams in such a device. This type of non-invasive measurement is performed by imaging the optical emission light radiated by the plasma – a technique that is routinely used at DESY [11].

Discharge plasma sources have routinely demonstrated plasma acceleration, laser guiding and focusing of charged particles in APLs at repetition rates of 1 to 10 Hz. However, in order to be successfully deployed in the next generation of plasma-based photon science and particle physics facilities, they will be required to operate at repetition rates of at least kHz.

Realising the next generation of plasma sources

The ADVANCE laboratory at DESY has been designed to rigorously investigate concepts required to develop discharge plasma sources capable of kHz-to-MHz operation. These concepts include:

- kHz-to-MHz high-voltage current pulse modulator systems
- Cutting-edge cell geometries capable of mitigating plasma and gas expulsion into vacuum
- Low-power kHz laser system to explore the guiding of laser pulses at high repetition rate
- State-of-the-art diagnostics including optical-emission spectroscopy, laser interferometry, cell and plasma temperature diagnostics as well as high-resolution current pulse monitoring
- Flexible and modular vacuum chambers capable of simultaneously supporting multiple plasma sources of varying type

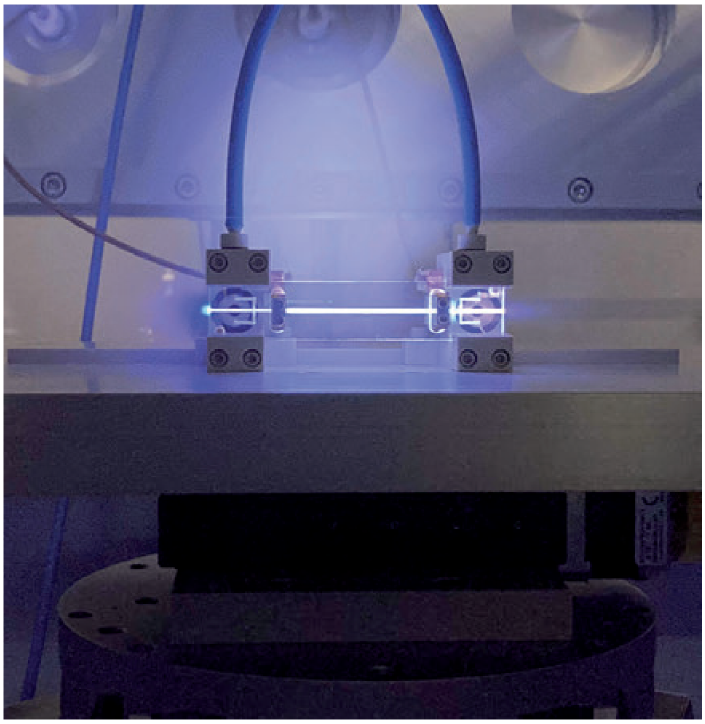

Figure 2

Plasma ignition by a high-voltage current pulse in the new ADVANCE lab at DESY

The ADVANCE lab has recently come online and is currently being commissioned (Fig. 2). The roadmap of the lab aims to drive forward the development of plasma sources at this new high-repetition-rate frontier and to act as a comprehensive test bed for both new and existing plasma sources, placing it at the centre of plasma wakefield R&D at DESY.

Thanks to the wealth of intellectual property amassed at DESY in plasma source technologies, investigations are also being carried out in the ADVANCE lab in collaboration with DESY's Innovation and Technology Transfer (ITT) department to explore commercialisation potentials. Through this, DESY strives to maintain its position as the world leader in bringing this essential future technology to a wider audience in industry and research.

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References:

[1] T. Tajima and J. M. Dawson, Phys. Rev. Lett. 43, 267 (1979)
[2] I. Blumenfeld et al., Nature 445, 741 (2007)
[3] M. Litos et al., Nature 515, 92 (2014)
[4] C. A. Lindstrøm et al., Phys. Rev. Lett. 126, 014801 (2021)
[5] E. Adli et al., Nature 561, 363 (2018)
[6] A. J. Gonsalves et al., Phys. Rev. Lett. 122, 084801 (2019)
[7] A. Butler et al., Phys. Rev. Lett. 89, 185003 (2002)
[8] D. Spence et al., J. Opt. Soc. Am. B 20, 138 (2003)
[9] S. Karsch et al., New J. Phys. 9, 415 (2007)
[10] R. D'Arcy et al., Philos. Trans. R. Soc., A 377, 20180392 (2019)
[11] J. M. Garland et al., Rev. Sci. Inst. 92, 013505 (2021)

Machine learning technology for hadron shower simulation

Can artificial intelligence beat detailed physics modelling?

Data analysis in high-energy physics depends heavily on the detailed simulation, using Monte Carlo methods, of the detector response to particles created in the physics interactions. These methods are based on extremely accurate modelling of the relevant physical effects that lead to the electronic signals seen in the detector. The modelling of these effects requires, in a large-scale effort, the development of surrogate simulations based on generative machine learning (ML) models, which produce 3D physics signals in the detector that are indistinguishable from the ones created with the detailed physics simulations. While the DESY FTX group has already been investigating the use of ML techniques to speed up the simulation of electromagnetic showers in highly granular calorimeters, current work extends this level of precision for the first time to the more challenging hadron-induced showers.

Introduction

The accurate simulation of physics interactions within complex detectors by means of state-of-the-art Monte Carlo techniques is an essential tool in high-energy physics (HEP). Starting from first conceptual designs for a new detector through the R&D phase to the real-data-taking periods, these simulations are used in all HEP experiments. The key point often lies in the exact modelling of the interaction of particles with the matter inside the detector, which results in the electronic signals that are eventually measured in the detector.

To this end, the Geant4 toolkit has been used in HEP for more than two decades, providing algorithms based on the best knowledge of the underlying physics processes. Although these algorithms are precise and accurate, the production of these simulations is increasingly costly in terms of computing time. This cost is already a potential bottleneck at the LHC, and the problem will be exacerbated by higher luminosity, larger amounts of pile-up and more complex and granular detectors at the High-Luminosity LHC and planned future colliders.

The largest fraction of computing resources is consumed by calorimeter simulations, where the particle energy is measured from a huge number of secondary decay products. Significantly speeding up this simulation time – at no loss of physics precision – could dramatically improve the scientific yield at less or constant cost.

Generative models

Generative models, a subfield of artificial intelligence (AI), have gained enormous attention in recent years with the prominent tasks of creating unique content that is indistinguishable from human-produced artefacts. These models learn the structure of the complex real-world data from examples and generate realistic synthetic examples that are bound by the same structure. The most famous examples of such models are generative adversarial networks (GANs) and variational autoencoders (VAEs).

The GAN architecture was introduced in 2014 and had remarkable success synthesising compelling real-world photo-realistic images, such as room interiors, album covers, fashion photos, human faces, etc. A traditional GAN consists of two networks: a generator and a discriminator separating artificial samples from real ones, which are trained against each other. One can imagine a GAN as a counterfeiter (generator) and a policeman (discriminator) competing against each other. In contrast to GANs, a VAE consists of an encoder, which maps input data to a latent space, and a decoder, which reconstructs the data from the latent space. If the probability distribution in latent space is known, it can be sampled from and used to generate new synthetic data.

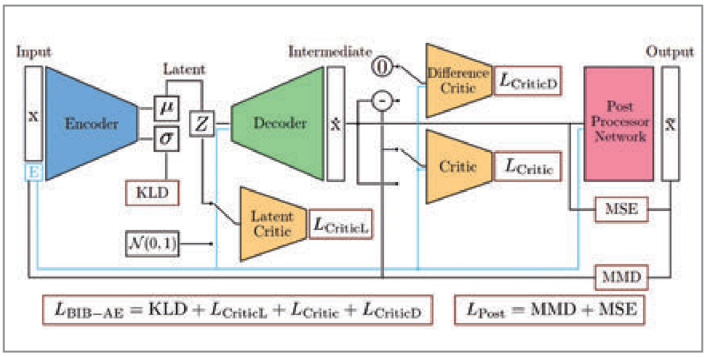

Figure 1

Schematic illustration of the BIB-AE setup with all the components

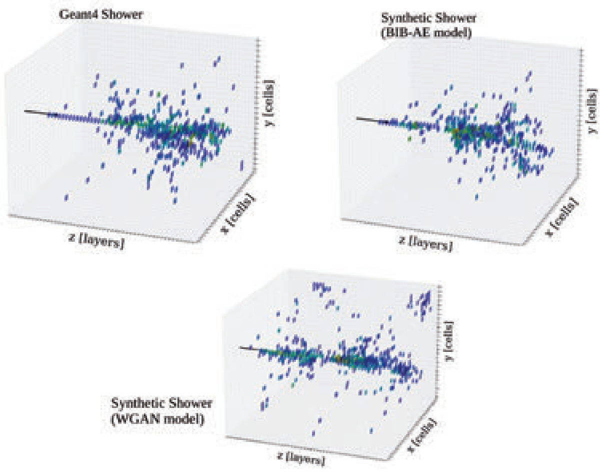

Figure 2

3D images of hadronic showers created by a 50 GeV charged pion in a highly granular hadron calorimeter with 3 x 3 cm² cell sizes. Upper left: Simulated with Geant4. Upper right and bottom centre: Synthetic showers generated with BIB-AE and WGAN generative models.

The bounded information bottleneck autoencoder (BIB-AE) is an overarching model that unifies commonly used generative networks [1]. In its essence, the model is an autoencoder that maps interaction events from data space to a lower-dimensional latent space and then back to data space (Fig. 1).

Fast shower simulation with generative models

The DESY FTX group, together with Universität Hamburg in the context of the cluster of excellence Quantum Universe and the Helmholtz Innovation Pool project ACCLAIM, has successfully applied GAN and BIB-AE models to highly granular electromagnetic calorimeter simulations [2], thereby getting one step closer to a real application at the LHC or future Higgs factories. Recently, the group has targeted the generation of hadronic showers, which, in contrast to their electromagnetic counterparts, reveal a much more complex structure and therefore pose a bigger challenge to the networks [3]. In parallel to the BIB-AE architecture, a variation of GANs called Wasserstein-GAN (WGAN) has been trained on a large set of hadronic showers. Both models are able to generate 3D images that are indistinguishable to the human eye from those simulated with detailed physics modelling in Geant4 (Fig. 2).

Getting the physics fast and right

If we were attempting to generate cute cat pictures, our work would already be done at this point. However, these shower images are eventually to be used as realistic substitutes in particle physics experiments. Therefore, it is essential to pay careful attention to relevant differential distributions and correlations so that the generated showers are indistinguishable for the physicists from showers simulated with Geant4 (or better, those actually measured in a real detector).

The DESY FTX group compared the differential distributions of high relevance, such as cell energies, hit occupancies, visible and reconstructed energies, for all studied architectures and Geant4. The BIB-AE model overlaps almost perfectly with the realistic simulation, while the WGAN model shows some slight deviations but is still reasonably close to Geant4 (Fig. 3).

The ultimate objective for employing generative models in particle physics is to reduce the time and cost per simulated event sample. To this end, the group benchmarked the per-shower generation time on both CPU and GPU hardware architectures. Evaluating the WGAN running on a modern GPU vs. Geant4 running on CPU, a speed-up by up to almost a factor of 10 000 was observed. While the BIB-AE produces showers of overall better quality than the WGAN, it is also one order of magnitude slower.

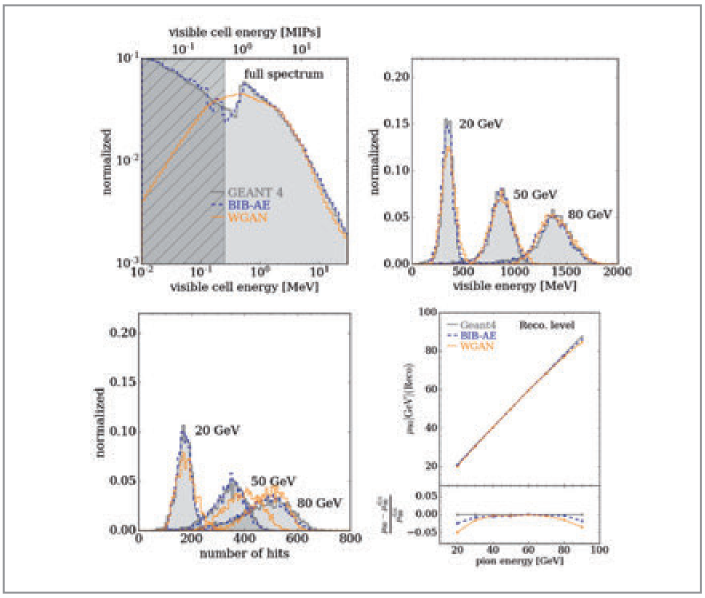

Figure 3

Comparison of various physics distributions of shower images generated with the generative models to those from realistic physics simulations with Geant4. The results in the bottom right plot are passed through a standard reconstruction software, which creates the high-level input for most physics analyses.

Fast calorimeter simulation with deep generative models is a very active field of current research in the international community, and DESY will continue to investigate the exciting possibilities of generative ML techniques. The coming years will show whether AI will already be able to beat the detailed simulations based on extensive physics knowledge and lead to fast application-ready generative models for highly granular calorimeters.

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References:

[1] S. Voloshynovskiy et al., arXiv:1912.00830 [cs.CV]
[2] E. Buhmann et al., Comput. Softw. Big Sci. 5, 13 (2021)
[3] E. Buhmann et al., arXiv:2112.09709 [physics.ins-det]

Any light particle searches

Zooming in to first data

The axion and other feebly interacting, very lightweight fundamental bosons are gaining increasing interest in the worldwide communities as solutions to long-standing and fundamental questions unanswered by the Standard Model of particle physics. In 2021, the installation of the first dedicated experiment at DESY was nearly completed.

What are the constituents of the dark matter in the universe? Why is charge conjugation parity (CP) symmetry conserved in quantum chromodynamics (QCD)? What is the next relevant energy scale beyond electroweak symmetry breaking? Many theories predict that this next energy scale cannot be reached in the foreseeable future by accelerator-based experiments, but requires new tools.

DESY is at the worldwide forefront of related theoretical and experimental activities in international collaborations.

Three experiments are being prepared at DESY:

- In 2021, construction of ALPS II was finished and commissioning started. ALPS II is a light-shining-through-the-wall experiment aimed at producing and

Figure 1

Operators from the accelerator division steering the first cooldown of ALPS II

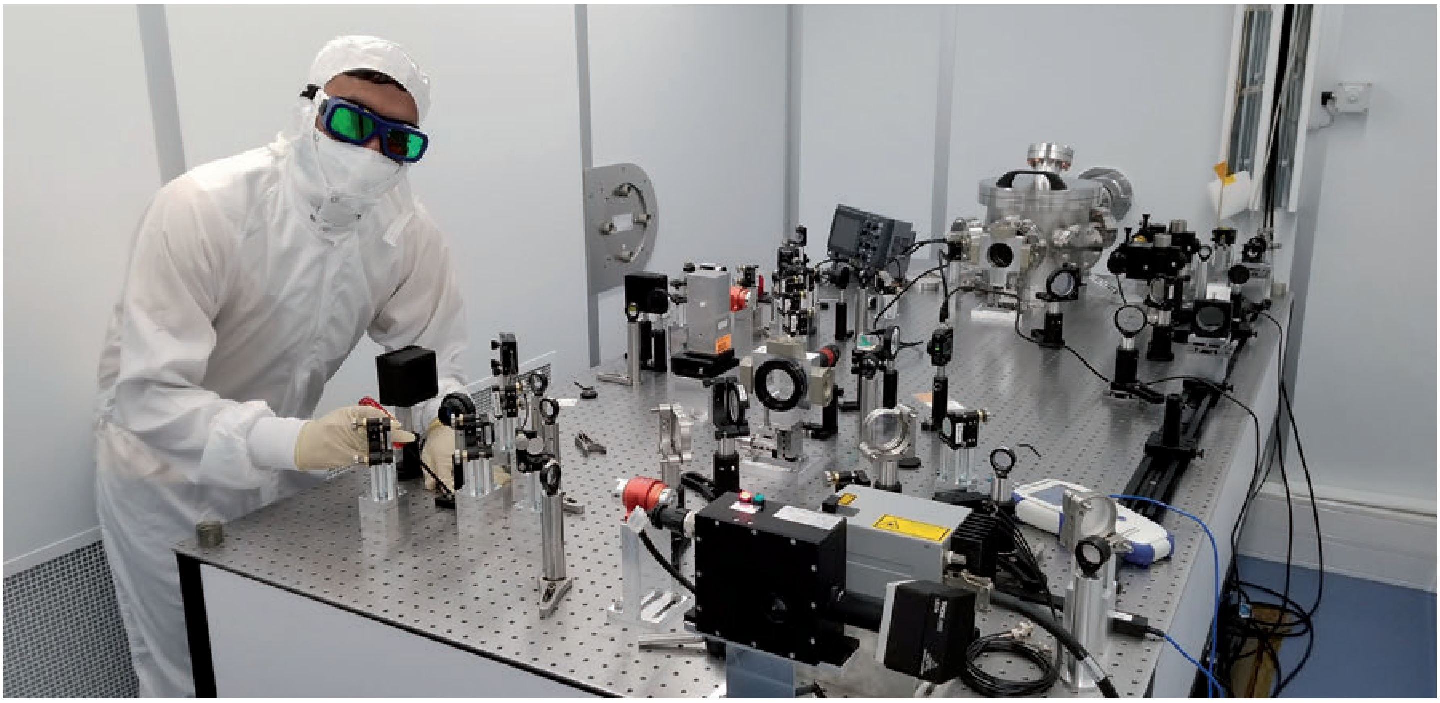

Figure 2

Installation of first optics components in the "North-Right" cleanroom to characterise the 250 m long cavity of ALPS II

detecting axions or similar particles with optical resonators embedded in strong magnetic dipole fields, located in the tunnel of DESY's former HERA accelerator (see previous annual reports).

- BabyIAXO, which will look for axions produced in the sun's core, was prepared for the official start of construction in 2022.
- MADMAX, designed to search for axions as constituents of ambient dark matter, entered a second prototype stage.

The physics motivation for all these experiments has constantly grown in the last years. In 2021, it became clear that the phase space for the QCD axion might be much larger than predicted by long-standing benchmark models. For relatively straightforward extensions of the Standard Model, the QCD axion might even be within reach of ALPS II [1].

ALPS II in the HERA tunnel

In 2021, the construction of the 250 m long ALPS II installations in the straight section of the HERA tunnel around the HERA North hall was completed: All magnets are now installed, aligned and connected electrically and to the cryogenics. The experimental vacuum has been established. The three cleanrooms for the cavity optics are operational and used for commissioning. All safety systems are operational, and the refurbishment of ALPS-related infrastructure in the HERA tunnel is nearly completed.

All these efforts culminated in the first, successful cool-down of the whole string of 24 HERA dipole magnets to their operating temperature of 4.2 K in mid-December (Fig. 1). This temperature was reached within three weeks, perfectly matching expectations. A test operation of the magnet string is planned for early 2022.

In spring 2021, the first optics components were installed in the ALPS II cleanrooms (Fig. 2). The alignment laser was steered through the whole magnet string in April, confirming the very accurate setup of all the dipoles led by DESY's survey group. Studies since then have been focusing on a roughly 250 m long optical cavity between the two outermost cleanrooms without the central "wall" of ALPS II, mainly to understand the environmental noise and characterise the performance of all the control loops.

A major achievement of the optics team was to demonstrate a stable "lock" of this cavity in June 2021 with a finesse around 5000, as expected from the properties of the (preliminary) cavity mirrors. Just from the cavity characteristics, the length of the cavity was measured to be 246.0625 m ± 0.0002 m. It was also demonstrated that the cooldown of the magnet string had no effect on the optical cavity: The aperture set by the beam pipe in the magnets was not altered by the drastic temperature change.

The control and data acquisition system of ALPS II is posing special challenges: As no triggers exist, such as those provided by particle bunches in accelerators for example, a truly continuous readout of many analogue-to-digital converter (ADC) channels is required. After several years of development, this system was installed, completed and demonstrated to be fully functional in late 2021. ALPS II will use DESY's dCache system for long-term data storage and its National Analysis Facility (NAF) for interpreting the data.

After the first data run with a heterodyne detection method, ALPS II plans to implement a photon-counting approach based on a superconducting transition edge sensor (TES, see previous annual reports). In 2021, the intrinsic noise of the TES was shown to be below 12 events within 20 days [2], fully meeting the ALPS II requirements. In 2021, Universität Hamburg became a new ALPS II collaboration partner contributing to further TES development.

In summary, although the pandemic brought many delays again in 2021 and made planning difficult, major and crucial milestones were reached nevertheless. A first science run of ALPS II is within reach in late 2022.

Meanwhile, first discussions on a later usage of the ALPS II infrastructure have started [3]. Ideas include means to increase the mass range in axion searches, an upgrade of the ALPS II optics, a first measurement of the vacuum magnetic birefringence and searches for high-frequency gravitational waves.

(Baby)IAXO

Another method is to search for axions generated in the sun, which would convert into photons inside a magnetic field. These photons in the energy range from 1 to 10 keV are then focused by special optics adapted from X-ray satellites and detected at the focal point by a dedicated detector. Obviously, the whole setup has to be mounted on a rotating support structure similar to optical telescopes and oriented towards the sun.

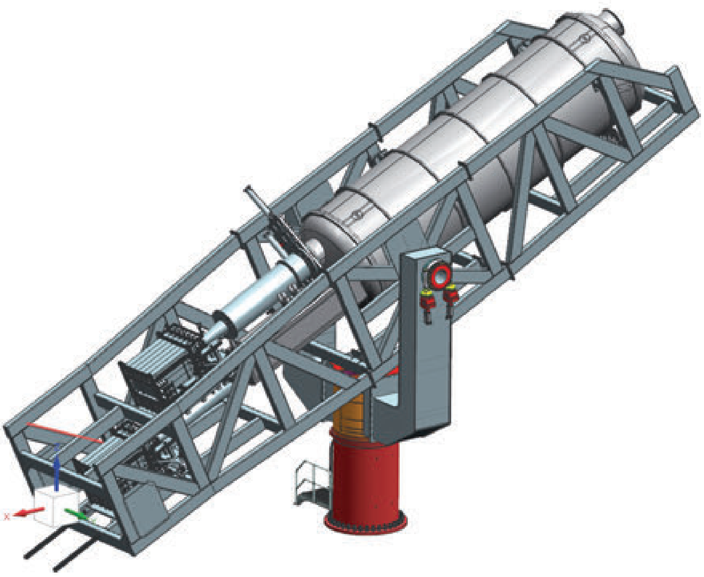

Figure 3

BabyIAXO ready for construction: the tower (displayed in red) with the mounted support frame holding the magnet cryostat (upper right), the X-ray optics (at the large gate valve), the vacuum tubes and the shielded detectors (lower left)

A search for solar axions was recently conducted by the CAST experiment, a so-called helioscope, at CERN. The International Axion Observatory (IAXO) is a proposal for a much larger helioscope with significantly increased sensitivity. The IAXO collaboration is now progressing with a prototype, called BabyIAXO, located at DESY (Fig. 3).

BabyIAXO will consist of a large superconducting dipole magnet with a maximum magnetic field of 3 T, a length of 10 m and a total mass of 48 t, in which the axion can convert into X-rays. The magnet is being designed by members of the ATLAS magnet group at CERN.

The magnet will have two inner bores, allowing for two independent "beam lines", including the optics and detectors at the focal point. The whole setup will be held by a large support frame made of stainless steel. The positioner of the medium-sized telescope (MST) prototype for the next-generation gamma-ray Cherenkov Telescope Array (CTA), which was in operation until January 2000 in Berlin-Adlershof, will be used as the structure and drive system of BabyIAXO. The experiment will be located in the HERA South hall, one of the experimental halls of the former HERA electron–proton collider at DESY.

Although significant progress was made on the design in 2021, there was unfortunately a serious setback. The original plan was to use a superconducting cable provided as an in-kind contribution by one of the collaborating institutes. Several test samples were sent to CERN and tested by the University of Twente in the Netherlands, with acceptable results. During the summer of 2021, however, all 27 cable spools – a total cable length of 55 km – were respooled and visually inspected. This inspection revealed many faults, which were not acceptable. A new cable therefore had to be selected and purchased instead of the originally foreseen conductor. Since aluminium-stabilised superconductors are no longer being produced, a copper-based conductor will now be used, resulting in some design changes due to the different masses and thermal properties of the stabiliser. The total mass of the magnet has now grown from 38 t to about 48 t.

The design of the structure and drive system is well advanced. The collaboration is presently in contact with companies concerning the manufacturing. One of the two X-ray optics, a spare flight module for the XMM Newton satellite, will be supplied on loan by the European Space Agency (ESA). The second optics will be custom-made and built by some of the collaborating institutes. The design is in progress. Significant advances have also been made on the detectors.

Studies are in progress trying to expand the physics case of (Baby)IAXO. In contrast to axion search experiments using lasers for axion generation, which are only sensitive to axion–photon couplings, helioscopes are sensitive to

Figure 4

Preparing a piezo motor test for MADMAX: The motors will be used to move the dielectric discs of the booster. They were qualified at DESY to also work at cryogenic temperatures in strong magnetic fields.

axions produced by axion–electron and axion–nucleon interactions. The collaboration recently completed a study on the production and detection of axions generated in the sun through the decay of iron-57 isotopes [4]. Another physics case would be the study of relic dark-matter axions by installing radio frequency cavities inside the inner bores of the magnet. This is presently pursued in cooperation with members of the RADES collaboration at CERN.

MADMAX

The third axion experiment at DESY will focus on relic dark-matter axions all around us. Again, such axions will enter a huge dipole magnet and convert to photons, here in the microwave regime. The conversion probability will be enhanced resonantly by a booster made of movable dielectric disks (see previous annual reports and [5]).

In 2021, a main focus of the MADMAX collaboration was to further demonstrate the technical feasibility of the experimental approach. CERN approved the request of the collaboration to perform booster measurements at the MORPURGO magnet located in the north area at CERN.

The booster task force founded in 2020 forced the decision to integrate intermediate steps with closed booster systems for a better understanding of the booster performance. First measurements were done with a small system in a 4.5 K environment. Further tests in a 1.6 T dipole magnet at CERN were approved in 2021 and scheduled for early 2022. During this test period, additional tests on a mechanical booster setup with three synchronised motors and one disk will be performed. Complementarily, a single-motor setup (Fig. 4) will be tested inside an ALPS II magnet in a 4 K and 5.3 T environment in January 2022, and the concept of gas cooling will be checked as well. The procurement process for the booster prototype vessel is finished, and a kick-off meeting with the selected company Noell is scheduled for January 2022.

The magnet development also passed an important milestone: The conductor performance was checked with a small test coil, and the conductor fulfilled the requirements on quench propagation.

The experimental infrastructure for the final MADMAX magnet is on a good track as well. The specification document for the cryoplatform – a distribution box with integrated subcooler – is close to being finished, and the start of tendering is planned for the first half of 2022.

In parallel, the ALPS group has set up a working group for cryogenic application techniques (large-scale and table-top experiments) and established the integration of models with COMSOL simulations to support experiments in their preparation and operation phases.

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References:

[1] A. V. Sokolov, A. Ringwald, PoS EPS-HEP2021, 178 (2022)
L. Di Luzio et al., JHEP 05, 184 (2021)
[2] R. Shah et. al., PoS EPS-HEP2021, 801 (2022)
[3] https://indico.desy.de/event/28588/
[4] L. Di Luzio et al., Eur. Phys. J. C 82, 120 (2022)
[5] MADMAX Collaboration, JCAP 10, 034 (2021)

Exploring physics at the quantum frontier

LUXE: a new experiment to study non-perturbative quantum electrodynamics

Laser Und XFEL Experiment, also known as LUXE, is an innovative physics experiment proposed to be built at DESY in Hamburg. It will bring together scientists from accelerator, laser and particle physics to study quantum electrodynamics (QED) in an unexplored regime. 2021 was a defining year for LUXE: The experiment's conceptual design report was released to the public in early spring and published in the summer [1], and the international collaboration was officially formed and elected its first spokesperson in the winter. The collaboration is now working on the technical design report in order to plan the installation of the experiment in the coming years.

QED is the theory that explains the interaction between light and matter. It was recognised early on by the physics community as having a significant impact on the field of elementary particles, and Sin-Itiro Tomonaga, Julian Schwinger and Richard P. Feynman were awarded the 1965 Nobel Prize in physics for their pioneering work on it [2]. Nowadays, it is one of the most well-tested physics theories.

Its predictive power mostly relies on perturbative calculations. Above a critical electromagnetic field value, known as the Schwinger limit, however, the perturbative expansion breaks down. This regime is called non-perturbative, or strong-field QED (SFQED).

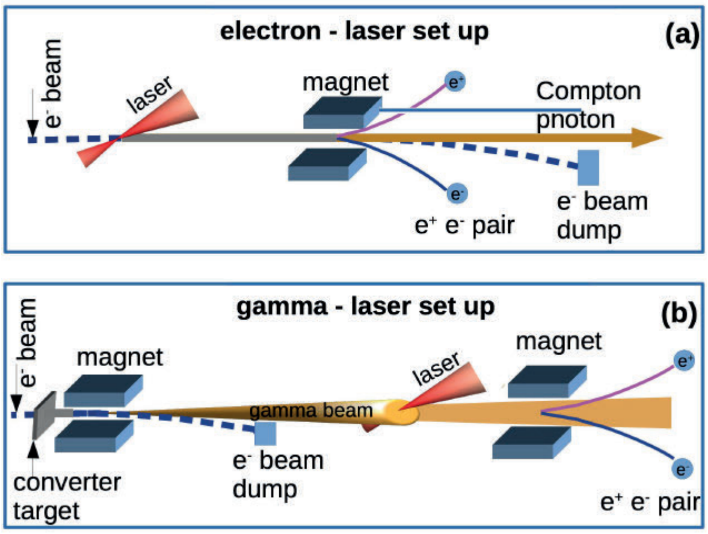

Figure 1

Conceptual sketches of the two LUXE running modes.

(a) Setup where the electron beam interacts directly with the laser beam.

(b) Setup where the electron beam is converted to a high-energy photon beam using a Bremsstrahlung target.

One of the physics processes predicted by SFQED is the creation of electron and positron pairs from the vacuum via the Breit–Wheeler process. Another typical SFQED process is non-linear Compton scattering, where the characteristic kinematic edges in the Compton spectrum shift as a function of the laser intensity, due to an increased effective mass of the electron.

LUXE aims to study SFQED by colliding the high-quality electron beam from the accelerator of the European X-ray Free-Electron Laser (European XFEL) with a state-of-the-art multiterawatt titanium–sapphire laser pulse. The strong field is created by the laser pulse and enhanced by the Lorentz boost of the electrons.

In such an environment, electron–positron pairs are predominantly created through a two-step process. First, a high-energy electron interacts with multiple low-energy photons from the laser, denoted γ_L, producing a high-energy Compton photon denoted γ_C and an electron (non-linear Compton interaction):

$e^- + n\gamma_L \rightarrow e^- + \gamma_C$.

Second, the Compton photon interacts with multiple low-energy photons from the laser, producing the electron–positron pair (Breit–Wheeler process):

$\gamma_C + n\gamma_L \rightarrow e^+ + e^-$.

LUXE is also planned to run in a mode where the laser will interact directly with high-energy photons, which will either be produced through Bremsstrahlung or through inverse Compton scattering. This γ–laser running mode is novel, since it probes the non-linear Breit–Wheeler process with pair production directly.

Sketches summarising the two data-taking modes of LUXE are shown in Fig. 1.

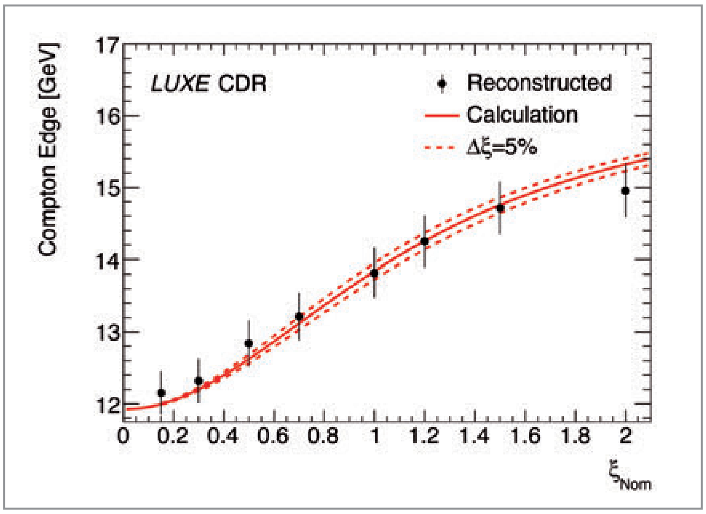

Figure 2

Measured energies at which Compton edges occur as a function of the laser intensity, obtained from MC simulations

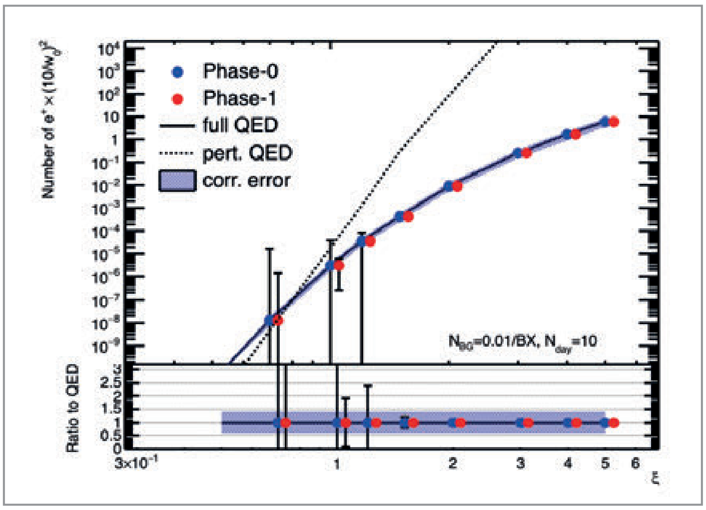

Figure 3

Measured number of positrons per laser shot as a function of the laser intensity normalised by the laser waist, obtained from MC simulations and compared to the full QED prediction and the perturbative QED prediction

The two main observables for testing SFQED in the experiment are therefore the measurements of the positron rate as a function of the laser intensity and the position of the Compton edges as a function of laser intensity.

Figure 2 shows the projective measurement of the energies at which Compton edges occur as a function of the laser intensity, obtained from Monte Carlo (MC) simulations. This measurement is challenging, since one needs to determine the flux of Compton electrons in a wide range, between 10^3 and 10^8 electrons per laser shot, depending on the laser intensity. To cover this wide dynamic range, robust detector technologies are foreseen, such as Cherenkov detectors or scintillating screens.

Figure 3 shows the projective measurement of the number of positrons per laser shot for two phases of the experiment, obtained from MC simulations. In Phase 0, the laser will have a power of 40 TW, and it will be upgraded to 350 TW in Phase 1. Expected measurements are compared to the perturbative and full QED predictions, demonstrating that it will be possible to distinguish between these calculations in most of the measured range accessible by the experiment. Once again, these measurements prove to be quite challenging because of the large dynamic range of the signal. To achieve a good linearity of the measurement precision, detectors such as calorimeters and trackers will be used.

The experiment will also offer the possibility to search for physics beyond the Standard Model in a high-intensity photon beam dump setup. Scenarios involving new phenomena, such as axion-like particles, have been investigated and found to offer a sensitivity better than or comparable to dedicated experiments [3].

In addition to the fascinating physics aspects, the construction and, later on, the full exploitation of the potential of this exciting experiment pose many experimental challenges that can only be tackled in a multidisciplinary environment. DESY is an ideal host platform where physicists, engineers and technicians from different areas can contribute their diverse expertise to solve technical puzzles and allow a smooth startup.

Among the technical challenges of LUXE are the design and installation of a complete new extraction and transfer line from the main European XFEL linear electron accelerator. Another challenge is the level of precision needed to control the laser intensity over a large number of shots. Knowledge of the focus can be explored to a much higher accuracy than in traditional laser experiments, since the laser pulse is to a large extent unperturbed by the electron beam. New diagnostic tools are being developed to reach this precision. Several teams at DESY are currently working on solving such technical challenges.

The results expected from LUXE will have a profound impact on our understanding of the fundamentals of particle physics. The realisation of LUXE poses interesting and challenging tasks across the disciplines of accelerator physics, laser physics and experimental particle physics.

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References:

https://luxe.desy.de
[1] LUXE Collaboration, Eur. Phys. J. Spec. Top. 230, 2445–2560 (2021)
[2] https://www.nobelprize.org/prizes/physics/1965/summary/
[3] LUXE-NPOD, arXiv:2107.13554 [hep-ph]

Machine learning meets HERA data

New insights on lepton–jet decorrelation from data recorded 15 years ago

The data recorded at DESY's HERA electron–proton storage ring, which was operated from 1990 to 2007, are preserved at DESY. The H1 collaboration, with contributors from DESY and other institutions all over the world, is still active modernising the analysis software and analysing the data at DESY's National Analysis Facility (NAF). In this article, the analysis of angular decorrelation between the scattered electron and jets is presented as an example, probing the region of small transverse-momentum imbalance. The work makes use of novel machine learning techniques for the data analysis and probes new predictions emerging from a field in theoretical physics that is under rapid development and is thus expected to profit from these new measurements.

Modernisation and analysis of HERA data

HERA was operated at DESY from 1990 to 2007, delivering unique data sets on electron–proton collisions at high energies to the experiments H1 and ZEUS. Such experimental data have to be processed and analysed on large computer systems in order to prepare them for comparisons with predictions, a process that can take years. Moreover, new questions may arise over time, which require another iteration on the original data.

The original H1 data have been preserved at DESY so they can be analysed there, making use of the NAF infrastructure. During the past years, physicists from all over the world have joined the H1 collaboration and are re-exploring the potential of these 15 year old data with novel analysis techniques in order to address questions that have emerged only after the end of data taking. At the same time, the H1 analysis software is constantly being modernised to keep pace with new computer systems and computing environments. A recent example is the integration in the LHC Computing Grid (LCG) environment [1], which provides standard interfaces to modern software packages. The same software environment is also used by present experiments at the LHC.

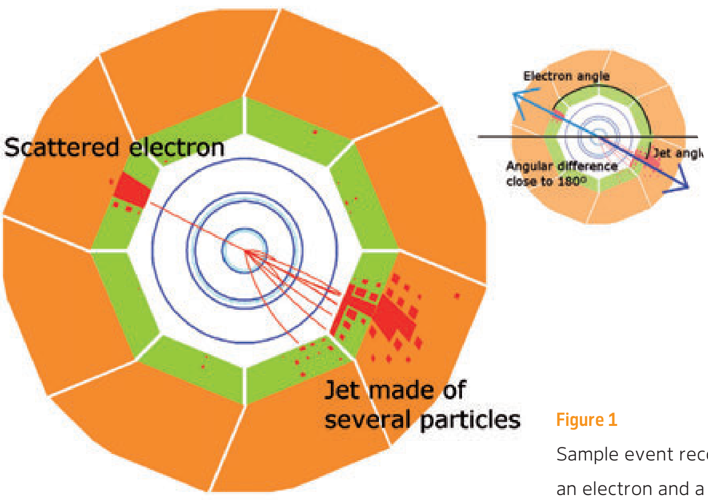

Figure 1

Sample event recorded with the H1 detector in 2006, showing an electron and a jet in back-to-back configuration

Electron–jet angular decorrelation

When electrons and protons collide, the electron can hit a quark in the proton. The electron is then scattered at an angle away from the beam axis. The amount of scattering is often characterised by the momentum transfer squared Q^2. The quark is scattered in the opposite transverse direction. In the experiment, the quark cannot be observed directly. Instead, it fragments into a jet of particles. These collimate around the original direction of the struck quark. The remnants of the proton also fragment into a number of particles, which travel along the beam axis and mostly escape detection. The transverse momentum of the scattered electron and the jet are balanced. Similarly, the azimuthal angular difference amounts to 180° – in other words, the azimuthal angles are fully correlated. This effect can be seen in Fig. 1.

Looking closer at this process, the theory of quantum chromodynamics (QCD) predicts modifications to this naive expectation. For example, a parton (a quark or a gluon) can radiate further partons, either before or after the interaction with the electron. These extra partons result in the

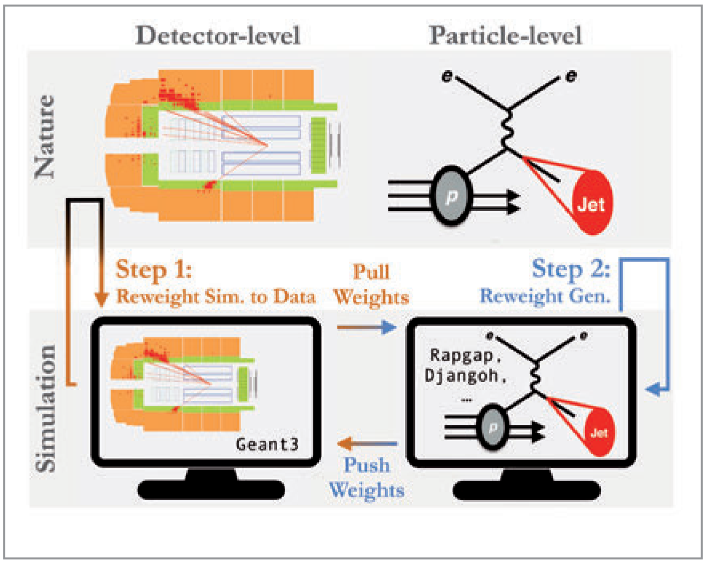

Figure 2

The MultiFold machine learning algorithm to mitigate detector effects, applied to H1 data. Each reweighting step is based on many hours of computing time, as it requires the training of a dedicated deep neural network. The two-step procedure is iterated five times.

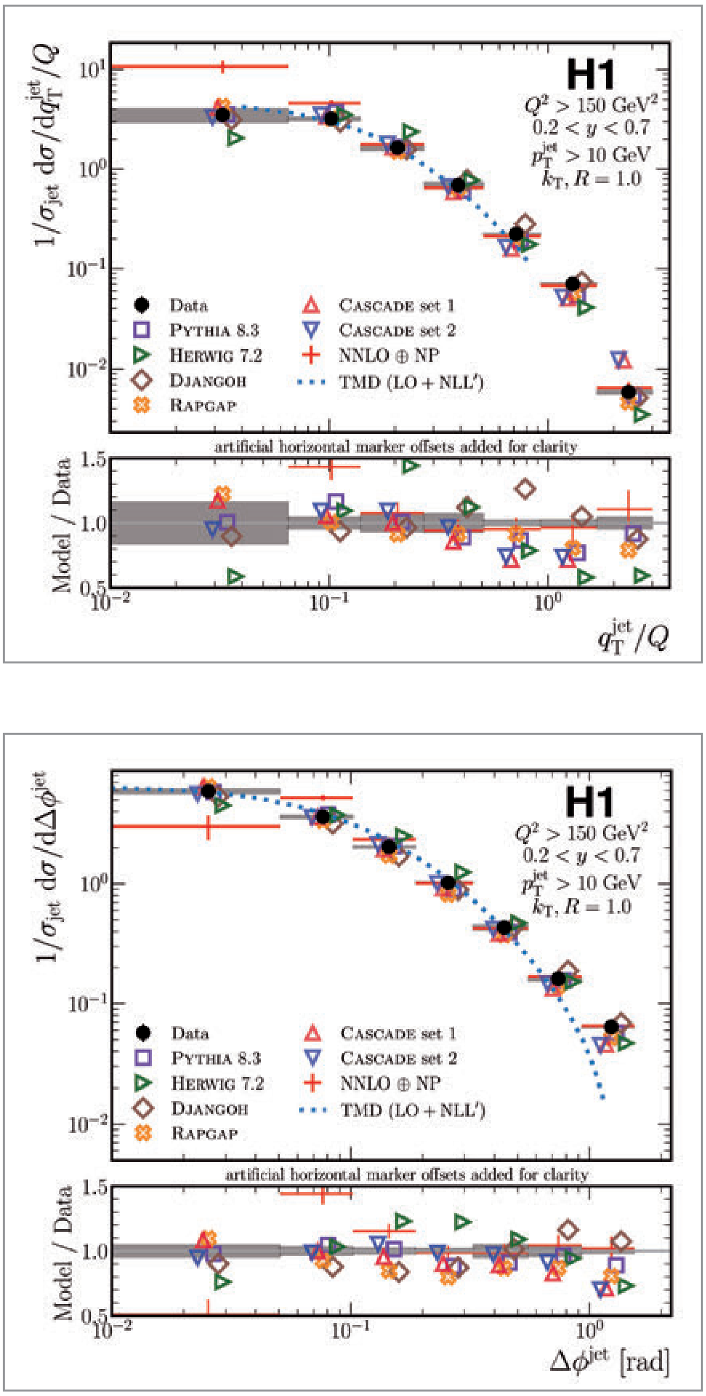

Figure 3

Interaction probability with respect to the electron–jet transverse-momentum imbalance on the vertical axis and azimuthal decorrelation on the horizontal axis. Shown are the data measured by the H1 collaboration in comparison with various predictions.

creation of extra particles, possibly forming additional jets. As a consequence, the scattered electron does not balance against a single jet in such events. Another option is that the struck parton carried some extra transverse momentum prior to the interaction with the electron. In that case, the expected momentum balance between electron and jet is violated by a small amount.

To test such predictions, the H1 collaboration has analysed the data with the help of machine learning techniques. The goal is to determine probabilities how frequently a certain transverse-momentum imbalance or angular decorrelation happens in electron–proton collisions. The machine learning algorithms, indicated in Fig. 2, are used here for the first time to remove detector effects from the observed data [2]. These “unfolded” data can be directly compared with new predictions without the need to model the details of the H1 detector again for each comparison.

Results

The interaction probability is measured as functions of the momentum imbalance q_T^{jet}/Q and the angular decorrelation $\Delta\phi$ (deviation from 180° expressed in radians) [3] and compared with predictions in Fig. 3. Traditional QCD predictions, based on collinear proton density functions and next-to-leading-order calculations (red lines), are able to describe the interaction probabilities at large q_T^{jet}/Q, but fail for small momentum imbalance. In contrast, novel predictions taking into account transverse-momentum-dependent distributions (dashed blue lines) are good at small momentum imbalance. The H1 data provide measurements over the full range and will thus stimulate further improvements to theory.

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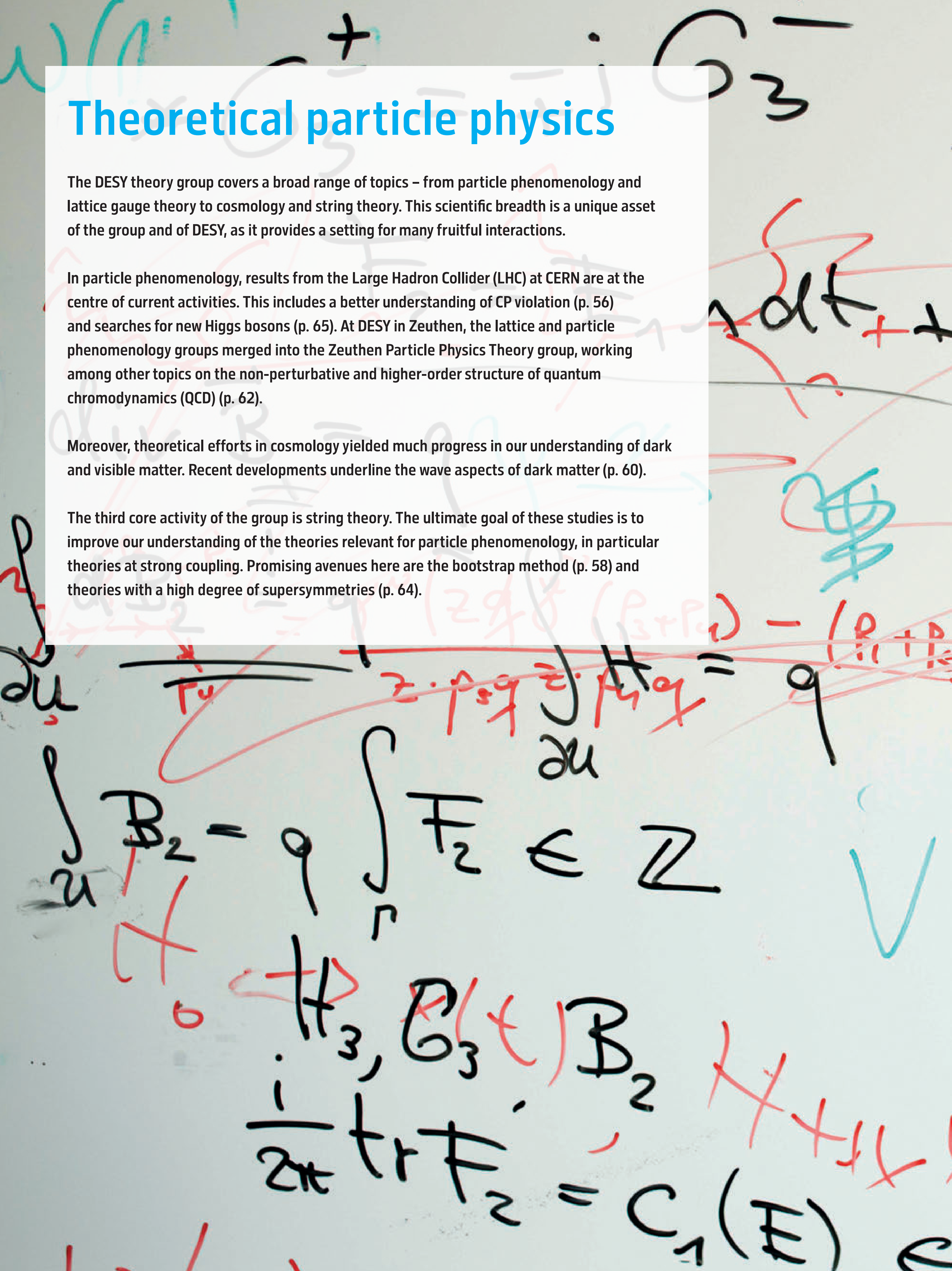
References:

[1] D. Britzger et al., EPJ Web Conf. 251, 03004 (2021)
[2] A. Andreassen et al, Phys. Rev. Lett. 124, 182001 (2020)
[3] H1 Collaboration, Phys. Rev. Lett. 128, 132002 (2022)



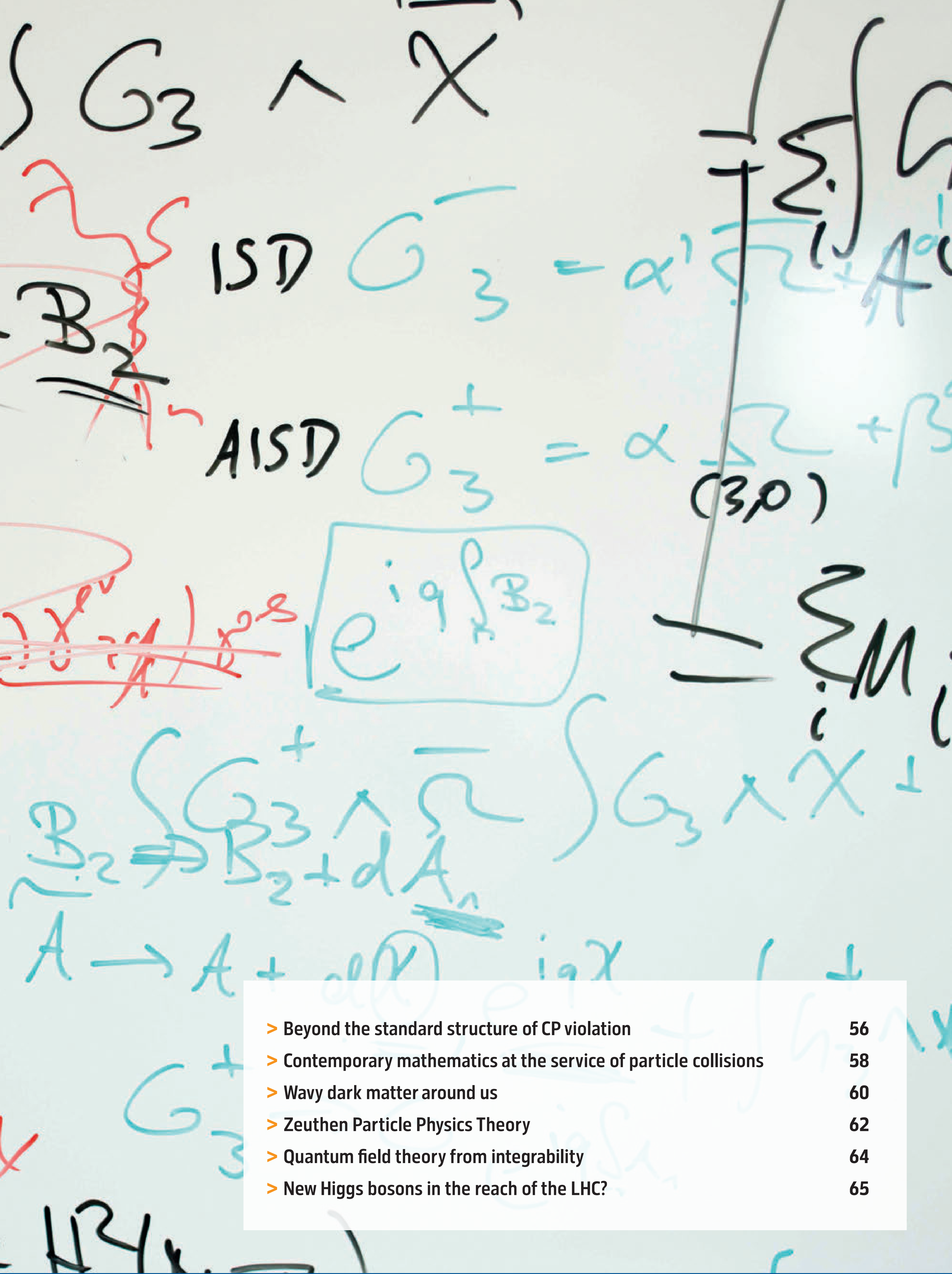
Theoretical particle physics

The DESY theory group covers a broad range of topics – from particle phenomenology and lattice gauge theory to cosmology and string theory. This scientific breadth is a unique asset of the group and of DESY, as it provides a setting for many fruitful interactions.

In particle phenomenology, results from the Large Hadron Collider (LHC) at CERN are at the centre of current activities. This includes a better understanding of CP violation (p. 56) and searches for new Higgs bosons (p. 65). At DESY in Zeuthen, the lattice and particle phenomenology groups merged into the Zeuthen Particle Physics Theory group, working among other topics on the non-perturbative and higher-order structure of quantum chromodynamics (QCD) (p. 62).

Moreover, theoretical efforts in cosmology yielded much progress in our understanding of dark and visible matter. Recent developments underline the wave aspects of dark matter (p. 60).

The third core activity of the group is string theory. The ultimate goal of these studies is to improve our understanding of the theories relevant for particle phenomenology, in particular theories at strong coupling. Promising avenues here are the bootstrap method (p. 58) and theories with a high degree of supersymmetries (p. 64).



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Beyond the standard structure of CP violation

Theoretical and phenomenological studies of CP symmetry breaking beyond the Standard Model

The CP symmetry, which combines the charge conjugation and parity symmetries, is very weakly broken in the Standard Model of particle physics. Therefore, observing large CP violations would be a clear sign of physics beyond the Standard Model. In the Higgs sector, bounds on new Yukawa-like couplings can be derived from the combination of LHC and electric dipole moment measurements. In addition, one can achieve a systematic and analytic study of order parameters for CP violation beyond the Standard Model, supplementing the small order parameter of the Standard Model. This approach makes the collective nature of CP violation as well as its degree of suppression explicit.

New physics, symmetries and CP

Measurements at high-energy facilities agree with the description provided by the Standard Model (SM), up to low-significance deviations. On the other hand, the SM does not describe neutrino masses, dark matter, baryogenesis and many more, and needs to be extended. It is therefore crucial to find departures from the SM predictions and gather information about physics beyond the Standard Model (BSM).

Signals of particular interest are those that the SM requires to be absent or very suppressed due to symmetry. For instance, baryon number is conserved in the SM, hence the observation of proton decay would signal new physics. Here, we focus on CP, the combination of charge conjugation and parity, which would imply that the equations describing the dynamics of particles also describe that of their antiparticles, provided one looks at them in a mirror. CP is almost a symmetry of the SM, meaning that large violations of CP would be unambiguous signs of new physics.

CP violation in the Standard Model

CP breaking in the SM has a subtle and predictive structure. Indeed, the most elementary interactions separately conserve CP: For instance, the couplings of top quarks to photons or to *W* bosons and bottom quarks preserve CP. Instead, the violation of CP in the SM is a collective effect, only arising when there are at least three generations of matter, when *W* bosons couple to all pairs of quarks of unit total electric charge, and when the masses of any two quarks of same charge always differ. This is quantitatively encoded in the order parameter for CP breaking of the SM, the Jarlskog invariant [1]:

$$
\begin{aligned}
J_4 \;&=\; (m_t^2 - m_c^2)(m_t^2 - m_u^2)(m_c^2 - m_u^2)(m_b^2 - m_s^2)(m_b^2 - m_d^2)(m_s^2 - m_d^2) \\
&\times\, \mathrm{Im}(V_{\mathrm{CKM,ij}} V_{\mathrm{CKM,kl}} V^*_{\mathrm{CKM,il}} V^*_{\mathrm{CKM,kj}})\;,
\end{aligned}
$$

where *m’s* refer to individual quark masses (normalised to a reference mass scale ≈ m_t), $V_{\mathrm{CKM},ij}$ refer to couplings of *W* bosons to the pair of quarks indexed by (*i*,*j*), and the imaginary part allows *W* bosons to differentiate between particles and antiparticles. When inserting measured values, most factors are found to be small, thereby making J_4, the strength of CP breaking in the SM, extremely suppressed. This has observable consequences: For instance, the SM predicts very slow rates for CP-violating decays of neutral kaons or a very small electron electric dipole moment (EDM). This is unlike most BSM models, which often break that pattern of CP violation and easily increase CP-breaking signals by orders of magnitude.

CP violation in effective approaches to BSM physics

In order to make generic statements, it is useful to consider effective approaches to BSM physics. Those are agnostic about the nature and dynamics of extra particles, whose impact is parameterised via generic modifications to the dynamics of the known particles. For instance, for heavy

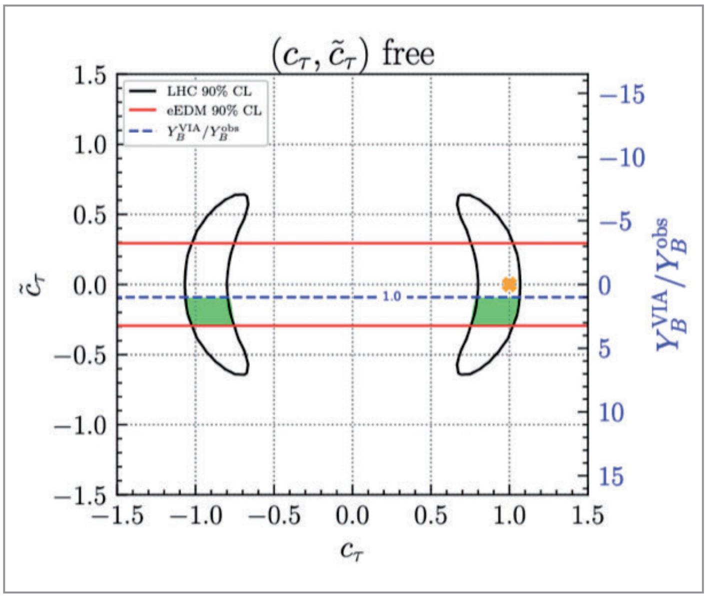

Figure 1

Bounds on the modified tau lepton–Higgs boson couplings [2]. The yellow cross indicates the SM point, and regions within the black and red lines are consistent with LHC and EDM bounds, respectively. In the green region, $\tilde{c}_\tau$ can also drive electroweak baryogenesis (the analysis accounts for the large theoretical uncertainties in baryogenesis computations).

extra particles, the interaction of pairs of charged leptons with a Higgs boson changes as follows:

$$y_{e,ij}\bar{e}_{L,i}e_{R,j}H \rightarrow y_{e,ij}\bar{e}_{L,i}e_{R,j}H + \frac{c_{eH,ij}}{\Lambda^2}\bar{e}_{L,i}e_{R,j}H|H|^2 ,$$

where $e_{L/R,i}$ denotes the components of the i-th lepton field, H the Higgs-boson field and Λ the mass scale of extra particles. y_e, c_{eH} are couplings that depend on the lepton pair (i,j), and the expression holds at leading order in a series expansion in $1/\Lambda$. Such generic modifications to the SM are constrained in many ways, e.g. by flavour observables.

An important class of probes concerns Higgs-boson physics, which is being probed at the LHC, and can still accommodate significant deviations from the SM predictions, in particular with respect to CP violation. Focusing on the aforementioned couplings of charged leptons to Higgs bosons and assuming that y_e,c_{eH} can be simultaneously diagonalised, one obtains the following Yukawa-like couplings:

$$y_{e,i}\bar{e}_i(c_i + i\tilde{c}_i\gamma_5)e_iH ,$$

where $\tilde{c}_i$ breaks CP. In the SM, c_i =1 and $\tilde{c}_i$ =0, and c_{eH} generates departures from these relations, which can be constrained by LHC measurements and bounds on the electron EDM. This has been performed in [2] for various (combinations of) couplings, an example being displayed in Fig. 1.

Actually, the assumption that y_e, c_{eH} are simultaneously diagonalised can be relaxed, since the off-diagonal entries of c_{eH} cannot contribute at leading order, as shown in [3] by a systematic analysis of all CP-breaking order parameters linear in c_{eH}. This does not hold for quarks, but in that case, the order parameters are suppressed by quark masses and quark–W boson couplings, hence their contribution is parametrically suppressed with respect to that of diagonal couplings. For instance, for down quarks, one finds the following off-diagonal order parameters:

$$J_{dH,ij} = \mathrm{Im}(m_{d,j}V_{\mathrm{CKM,ki}}V^*_{\mathrm{CKM,kj}}c_{dH,ij}) ,$$

where c_{dH} is defined similarly to c_{eH}. A systematic and analytic analysis of CP-breaking order parameters for all possible leading-order deviations from the SM can be found in [3]. It pinpoints the collective structure of BSM CP breaking and its implications for the strength of CP violation.

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References:

[1] C. Jarlskog, Phys. Rev. Lett. 55, 1039 (1985)
[2] H. Bahl, E. Fuchs, S. Heinemeyer, J. Katzy, M. Menen, K. Peters, M. Saimpert, G. Weiglein, arXiv:2202.11753 [hep-ph]
[3] Q. Bonnefoy, E. Gendy, C. Grojean, J. Ruderman, arXiv:2112.03889 [hep-ph]

Contemporary mathematics at the service of particle collisions

Cluster algebras and integrability promise to overcome the limitations of Feynman diagrams

Efficient predictions of the outcome of elementary particle collisions are vital for confronting our current understanding of nature with experiment. These predictions may in principle be obtained with the help of Feynman diagrams, which visualise mathematical expressions known as Feynman integrals. However, their evaluation becomes notoriously challenging as the precision of the prediction increases, and the entire framework breaks down when the particles are interacting strongly. Members of the DESY theory group are developing novel mathematical tools that offer exciting prospects for circumventing these important practical and conceptual obstacles.

Cluster algebras in quantum chromodynamics

In our quest to find what the elementary constituents of matter are and how they interact, a crucial role is played by collider experiments, where these constituents smash against each other at nearly the speed of light, and we observe what comes out. New physics can then be discovered by comparing these outcomes with their theoretical prediction, which at its core is captured by physical quantities known as scattering amplitudes.

Thanks to the pioneering work of Richard Feynman and many other theoretical particle physicists, by now there exists a well-established framework for computing scattering amplitudes in quantum field theory when the particles are interacting weakly. This approach relies on Feynman diagrams, which represent all possible ways in which the incoming particles can transform into the products of the collision, by exchanging other unobserved, "virtual" particles. As the energy and momentum of these virtual particles may be anything that the laws of nature allow, one additionally has to integrate over all their possible values. Thus, Feynman diagrams correspond to mathematical expressions known as Feynman integrals. One of the main challenges for obtaining theoretical predictions, however, is that these integrals are famously hard to evaluate.

As described in the *DESY Particle Physics 2017* report, for a symmetric cousin of quantum chromodynamics (QCD), i.e. the theory of the strong force, a significantly more efficient "bootstrap" method has been developed, which bypasses the complexity of Feynman integrals and instead constructs amplitudes by exploiting their analytic structure. The theory in question is known as maximally supersymmetric Yang–Mills (MSYM) theory. As reviewed in more detail in Chapter 5 [1] of an extensive amplitudes review by the EU

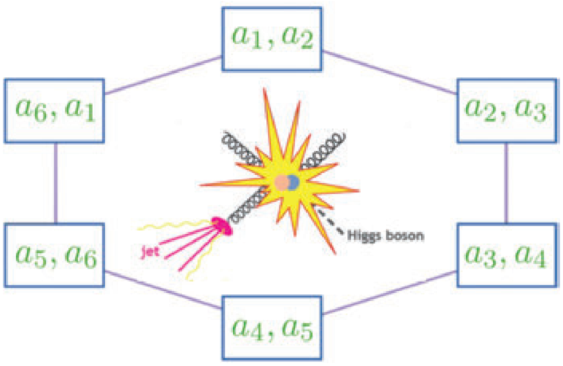

Figure 1

The singularities of two-loop Higgs production amplitudes in the heavy-top limit of QCD are encoded in the six a_i variables of the C_2 cluster algebra. Adaptation of image by Carolin Leyck / MPP Munich.

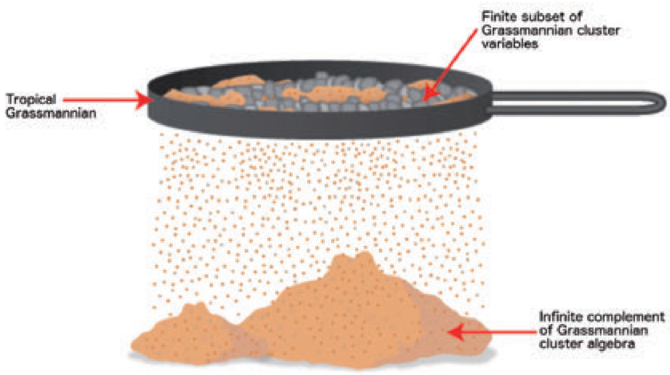

Figure 2

Schematic depiction of how the infinity of cluster algebras associated with MSYM amplitudes of multiplicity $n > 7$ can be tamed with the help of tropical Grassmannians

Scattering Amplitudes from Geometry to Experiment (SAGEX) Innovative Training Network, of which DESY is a member, the scattering amplitudes of this theory have been bootstrapped to unprecedented accuracy.

Essential input for enabling the method comes from beautiful mathematical objects known as cluster algebras, consisting of certain variables that have been found to encode the singularities of the amplitude. Until recently, a factor deterring the wider applicability of the bootstrap was that the relevance of these objects was established only in the realm of MSYM. Excitingly, this changed with Ref. [2], which reported the discovery that cluster algebras also underlie the analytic structure of a host of more general Feynman integrals and physical processes of QCD. As shown in Fig. 1, this most notably includes amplitudes for the production of the last elementary particle to be discovered, the Higgs boson! The potential of this discovery for realistic applications was also recognised by the cluster of excellence Quantum Universe at Universität Hamburg and DESY, which conferred Ref. [2] a Best Paper Award in September 2021.

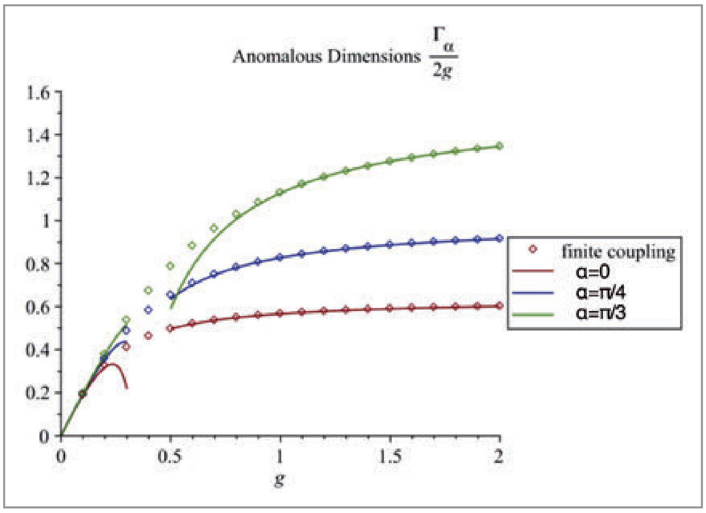

Figure 3

The six-gluon amplitude in the "origin" limit at finite coupling g. Its non-trivial coupling dependence is encoded in Γ_0, $\Gamma_{\pi/3}$ depicted in the plot. Points correspond to the numerical evaluation of their exact expression and lines to their analytic weak- and strong-coupling expansions. For comparison, the integrability-predicted cusp anomalous dimension $\Gamma_{\pi/4}$ is also shown.

Singularities from tropical geometry

Even in the realm of MSYM theory, however, it is well known that cluster algebras are not the end of the story, as those that are associated with amplitudes of $n > 7$ particles become infinite and are therefore unable to provide any meaningful singularity predictions. Fortunately, researchers of the DESY theory group have proposed a natural resolution of this longstanding puzzle, simultaneously with other groups at the Institute of Advanced Study in Princeton, USA, and at the University of Southampton, UK, with the help of geometric spaces known as tropical Grassmannians.

In particular, it was realised that cluster algebras triangulate tropical Grassmannians and that the nature of infinities of the former can be interpreted as a redundant dissection of the latter, analogous to a process of splitting triangles into smaller triangles without ever terminating. As depicted in Fig. 2, tropical Grassmannians could thus be used in the first instance as a sieve that selects a finite subset of cluster variables or, in other words, potential amplitude singularities. While initially worked out mostly for $n = 8$, the more recent extension of this natural resolution to in principle any multiplicity n [3] was also honoured with a Best Paper Award by the cluster of excellence Quantum Universe in March 2022.

The origin of non-perturbative scattering

Finally, another intrinsic limitation of Feynman diagrams is that they are unable to describe important physical phenomena occurring when the interaction strength, or coupling, is strong. Remarkably, in the large-colour approximation of MSYM theory, this is still possible thanks to integrability, namely the property of a physical system to possess as many conserved quantities as degrees of freedom.

For scattering amplitudes, this property was initially well understood only in a particular collinear limit. In *DESY Particle Physics 2017*, we presented our success in harnessing its power also in the phenomenologically relevant high-energy multi-Regge limit. More recently, we have led an international collaboration that exposed yet another integrable limit, corresponding to the "origin" where certain physically motivated kinematic variables of the six-particle amplitude approach zero. As may be seen in Fig. 3, the latter's dependence on the coupling g enters through certain anomalous dimensions Γ_α, which have been determined exactly for any value of g [4]!

The analysis of similar limits at higher multiplicity is currently under way. In a broader perspective, over the past years, members of the DESY theory group have made great progress towards both solving the simplest cousin of QCD and identifying potentially universal properties with broader applicability. We are thus optimistic that these ambitious conceptual and practical goals are within reach.

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References:
[1] G. Papathanasiou, arXiv:2203.13016 [hep-th]
[2] D. Chicherin, J.M. Henn and G. Papathanasiou, Phys. Rev. Lett. 126, 091603 (2021)
[3] N. Henke and G. Papathanasiou, JHEP 10, 007 (2021)
[4] B. Basso, L.J. Dixon and G. Papathanasiou, Phys. Rev. Lett. 124, 161603 (2020)

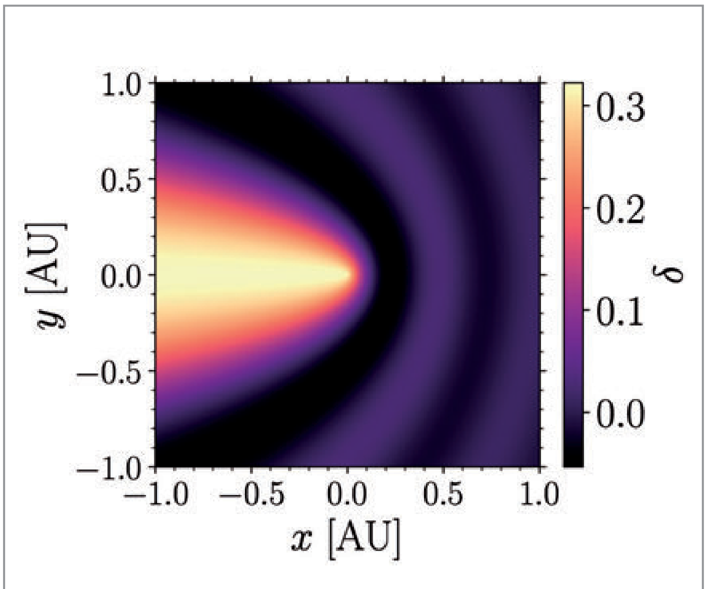
Wavy dark matter around us

How does the sun deform a local map of wave dark matter?

Light bosonic dark matter is an attractive dark-matter candidate. Being much lighter than any Standard Model (SM) particles that we know of, this dark-matter candidate behaves as a collection of classical waves rather than an individual particle. Members of the DESY theory group have investigated how the local distribution of wave dark matter is deformed by the sun and shown how this gravitational deformation could potentially change signals in terrestrial detectors of wave dark-matter detection experiments.

Dark matter is one of the most compelling hypotheses in cosmology and astrophysics, explaining a wide variety of observations, including the cosmic microwave background, large-scale structures, gravitational lensing, rotation curves and many others. Yet, its nature is a mystery. Two key questions would be: What's its mass? And how does it interact with other particles, such as protons and electrons?

As there are an infinite number of possible answers to these questions, theoretical input is useful to prioritise our efforts for dark-matter searches. Especially, since the specific design of direct-detection experiment is often sensitive to a limited range of dark-matter mass and a specific coupling of dark-matter and SM particles, having well-motivated dark-matter models would help us to narrow down the most interesting region of parameter space.



Wave dark matter is an interesting dark-matter candidate. It corresponds to light bosonic dark matter with a mass smaller than several electronvolts. Given the measured value of the local dark-matter density, there is more than one particle within a de Broglie wavelength of dark matter, and as a result, dark matter behaves more like a classical wave rather than a particle, hence the name "wave" dark matter. Wave dark-matter candidates can naturally arise in many scenarios beyond the SM. The quantum chromodynamics (QCD) axion is one example, which was originally proposed as a solution to the strong CP problem in the SM. A relaxion is another example, which was originally proposed as a solution to the electroweak scale hierarchy problem.

Over the past decades, there have been extensive efforts towards direct detection of wave dark matter. Direct-detection experiments attempt to directly measure

Figure 1

Local density for wave dark matter with a wavelength of 1 AU. The brighter region is the region where there is more dark matter compared to the darker region. In this figure, dark matter is moving from the positive *x*-axis to the negative *x*-axis at speed v = 240 km/s.

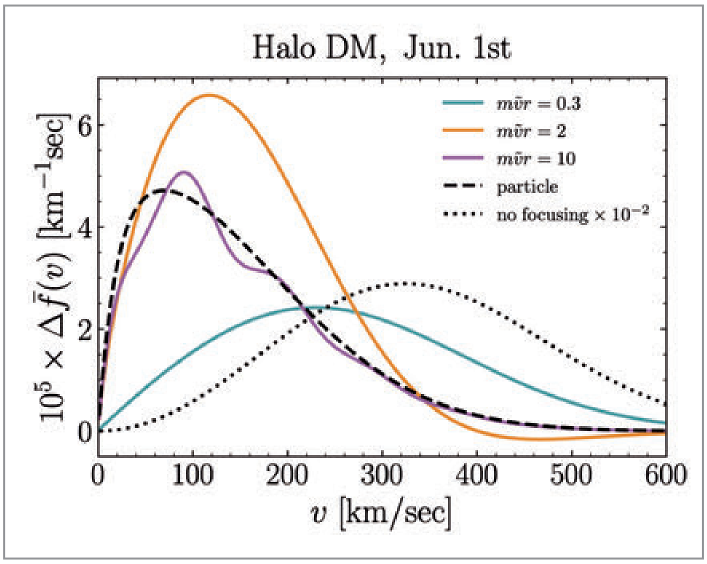


Figure 2

Dark-matter (DM) speed distribution, modified by the gravitational potential of the sun

signals arising from interactions between dark matter and the SM particles. As these experiments rely on signals from local dark matter in the solar system, a correct modelling of local dark matter is crucial for interpreting the experimental data. A common way to model local dark matter is to assume that the velocity of dark matter is distributed according to the normal distribution. This is referred to as the standard halo model.

The standard halo model provides a simple way to model the bulk dark-matter halo, but it does not account for several aspects of the local dark-matter distribution. First, it does not include dark-matter substructures in the solar system. Such dark-matter substructures have a distinctive kinematic structure compared to the bulk dark-matter halo, providing a different signal in terrestrial detectors. Second, the standard halo model does not account for the gravitational potential of the sun. This deflects the trajectory of dark matter near the solar system, focusing dark matter into a narrow range of space. This gravitational focusing changes not only the local density but also the speed distribution of dark matter. More interestingly, each dark-matter substructure responds differently to the gravitational potential, as they have different velocity. Given that recent observations find an increasing number of dark-matter substructures, it is important to estimate the gravitational focusing effects of the dark-matter halo and substructures.

Researchers in the DESY theory group have investigated the gravitational deformation of wave dark matter in the solar system [1]. Wave dark matter shows characteristic patterns in the local density (Fig. 1) and in the speed distribution (Fig. 2). Contrary to particle-like dark matter, the local density is smoothened over the scale of de Broglie wavelength of dark matter, as one can see in Fig. 1, while the speed distribution in Fig. 2 exhibits a certain oscillating patterns, which is again due to the wave nature of dark matter. The wave nature of the local density and speed distribution is most apparent when the wavelength of dark matter is about an astronomical unit or when dark-matter substructures have small velocities.

The enhanced local density and speed distribution will certainly change the signal shapes in the detectors. Including such gravitational focusing effects is important for modelling local dark matter with a few-percent-level accuracy. Upon detection of dark matter, accounting for gravitational focusing effects will become even more important for a correct estimation of dark-matter halo parameters and of its coupling and mass.

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Reference:

[1] H. Kim, A. Lenoci, arXiv:2112.05718 [hep-ph] (submitted to Phys. Rev. D.)

Zeuthen Particle Physics Theory

Theoretical perturbative and non-perturbative particle physics at DESY in Zeuthen

The ZPPT group consists of the Collider Phenomenology group (CPG) and the Lattice group at DESY in Zeuthen, the latter also being a research group at the John von Neumann Institute for Computing (NIC). While the CPG performs high-loop perturbative calculations, the NIC group studies non-perturbative physics of the Standard Model. Both groups aim to reach high-precision results for the input and interpretation of ongoing and planned high-energy and nuclear physics experiments worldwide. This concerns non-perturbative matrix elements in *B* physics and hadron structure on the lattice side, as well as multiloop calculations for observables within the Standard Model on the perturbative side. ZPPT also has a strong focus on algorithmic and methodological developments to improve the calculations, leading to even higher precision. This article presents two particular results, namely Symanzik's effective theory and a novel approach to mitigate negative weights in event generators.

Asymptotic approach to the continuum of lattice QCD spectral observables

Quantum chromodynamics (QCD), the fundamental theory of hadrons and nuclei, can be treated perturbatively at small distances (or large momentum transfers μ), where the running coupling $\alpha_s(\mu)$ is small (asymptotic freedom). Discretising the theory on a regular space–time lattice with spacing a further provides a rigorous definition of QCD. This lattice approach has been developed in the last decades, and, for many observables, a numerical computation by Monte Carlo "simulations" yields rather precise results. Since the lattice spacings are not orders of magnitude smaller than the typical QCD scales of order 1 fm, care has to be taken to understand the discretisation errors and remove them by extrapolation.

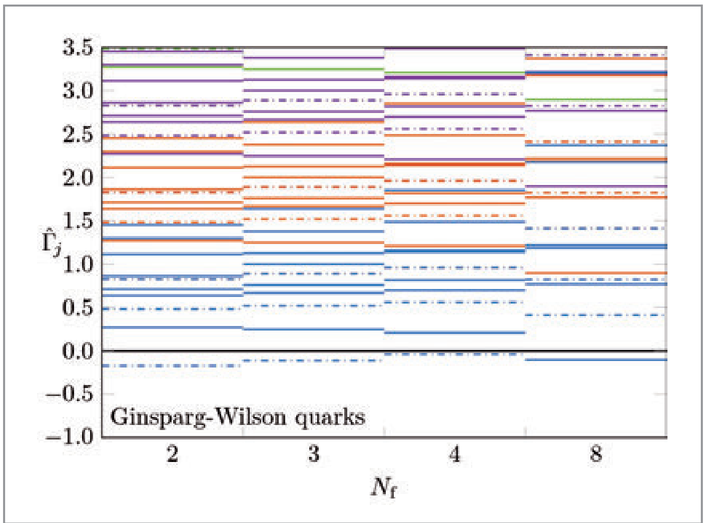

Figure 1

Spectrum of the anomalous dimension matrix for Ginsparg–Wilson quarks

The asymptotics of these effects can be obtained analytically due to the vanishing of the strong coupling in this limit. To obtain this explicit form, one formulates an effective field theory, Symanzik's effective theory, given by adding local dimension six operators into the continuum path integral, and subsequently obtains the coefficients of these operators by a matching calculation. In the end, one obtains the result in terms of renormalisation scale invariants and coefficient functions that evolve with the running coupling.

The operators mix under renormalisation, and the results are best described by looking at the spectrum of the anomalous dimension matrix obtained by this calculation. Figure 1 shows this spectrum for the case of Ginsparg–Wilson fermions only including fermionic operators. N_f indicates the number of quark flavours. The behaviour is qualitatively the same for other quark actions, but additional, chiral-symmetry-violating operators lead to a somewhat denser spectrum.

The main result [1, 2] is good news for lattice gauge theory: We find no significant negative eigenvalue that would slow down the approach to the continuum limit.

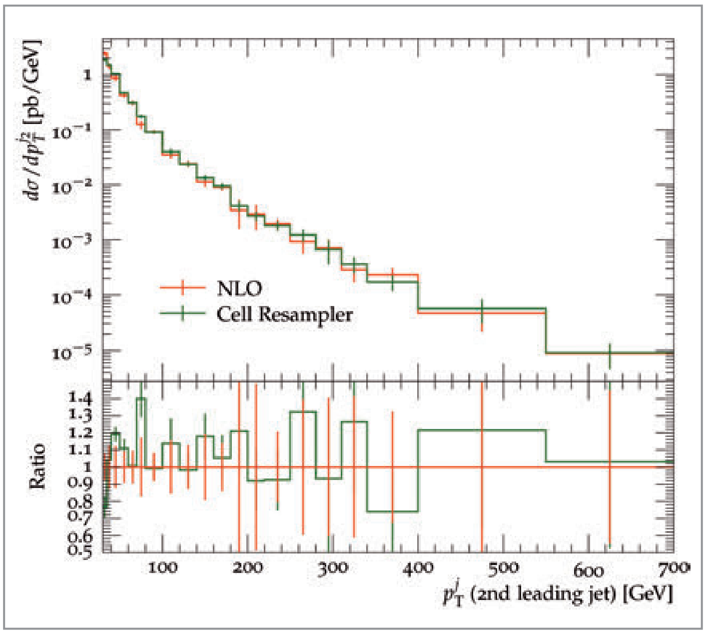

Figure 2

Distribution of the transverse momentum of the second-hardest jet before and after cell resampling

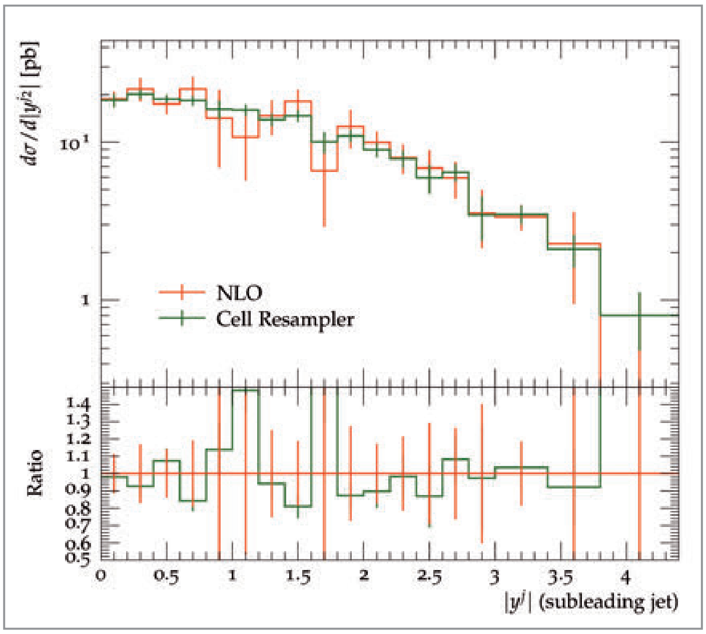

Figure 3

Distribution of the rapidity of the second-hardest jet before and after cell resampling

Optimising event simulation for the LHC

DESY has a strong involvement in the ATLAS and CMS detector experiments at the LHC at CERN. These experiments rely on an accurate and efficient simulation of collision events. However, state-of-the-art event generators inflate the number of events that have to be considered, rendering event simulation computationally very costly. The cause is counter-events, which have to be subtracted from the final event number to correct for overcounting in intermediate steps. A new method can be used to eliminate the need for a large fraction of these counter-events early on.

Cell resampling

The simulation of collision events at the LHC proceeds in several steps, starting with event generation in fixed-order perturbation theory. Already here, calculations beyond the leading-order approximation generally introduce counter-events, which are subtracted to avoid overcounting in predicted cross sections. This means that a larger number of events have to be considered in later steps, in particular in the computationally very expensive simulation of the detector response.

The idea of cell resampling [3] is to introduce an additional step into the event simulation chain, in which the effect of counter-events is absorbed in the contribution from similar regular events. Counter-events are grouped into small cells with other events. Within each such cell, the contribution from each event is adjusted to be positive, preserving the total contribution of the complete cell. Afterwards, much less events are needed to achieve the same statistical accuracy.

Predictions for observables are only unaltered if the events within each cell are indistinguishable in real-world measurements. In practice, one requires a small cell radius in terms of a metric that reflects experimental sensitivity. This ensures that any change in the predictions is small compared to other uncertainties.

Application

To demonstrate the performance, a sample with a large fraction of counter-events was obtained by predicting the production of a *W* boson together with two jets at next-to-leading order in perturbation theory using the Sherpa event generator. After cell resampling, the contribution from counter-events was reduced by more than an order of magnitude. Predictions for observables were preserved within statistical uncertainties, as shown for two examples in Fig. 2 and 3.

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References:

[1] N. Husung, P. Marquard, R. Sommer, arXiv:2111.04679 [hep-lat]
[2] N. Husung, P. Marquard, R. Sommer, arXiv:2111.02347 [hep-lat]
[3] J. R. Andersen, A. Maier, arXiv:2109.07851 [hep-ph]

Quantum field theory from integrability

Probing strongly coupled quantum field theory and quantum gravity

Quantum field theory (QFT) is arguably the most successful framework of theoretical physics. It describes a broad range of phenomena, from condensed-matter systems to elementary particle physics, with spectacular precision. Yet, our current formulation of QFT is incomplete: We lack tools to address strongly coupled quantum systems or to describe quantum gravitational interactions. A new Emmy Noether Independent Junior Research Group at DESY uses powerful methods from the theory of integrable models to probe these elusive parts of QFT.

While QFT at weak coupling is extremely well understood, we have very little control over it once the coupling becomes large. The $N = 4$ super Yang–Mills (sYM) theory is a perfect model to advance on this severe conceptual challenge. Its enhanced symmetry makes it especially accessible, yet it is sufficiently complex to offer insights about more realistic theories. Its importance is further emphasised by the AdS/CFT correspondence, which provides a powerful approach to both strongly coupled gauge theory and a theory of quantum gravity (string theory).

Most notably, $N = 4$ sYM becomes integrable in the 't Hooft planar limit. Traditionally rooted in the realm of statistical mechanics, integrability methods have been developed to admit exact descriptions of the theory's observables (correlation functions, Wilson loops, scattering amplitudes) all the way from weak to strong coupling. One state-of-the-art approach amounts to a completely new formulation of planar gauge theory in terms of hexagon form factors, planar integrable patches of string worldsheet that are glued together to form complete correlation functions. Strikingly, this approach also applies to non-planar terms and hence captures quantum gravitational interactions.

The goals of the Emmy Noether group are (i) to further develop these new approaches in order to probe gauge theory with generic coupling as well as quantum gravity as deeply as possible and (ii) to generalise these new methods to less supersymmetric and more realistic theories.

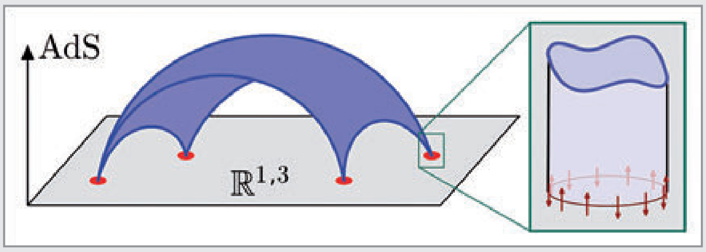

Figure 1

A correlation function on the Minkowski boundary equals a string amplitude in AdS. Detail: The string worldsheet is sourced by a boundary single-trace operator that gets mapped to an integrable spin chain.

Emmy Noether Independent Junior Research Group

"Solving Field Theory with Integrability"

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References:

[1] https://www.desy.de/~bargheer/
[2] https://gepris.dfg.de/gepris/projekt/460391856

New Higgs bosons in the reach of the LHC?

Investigating possible indications in two scenarios beyond the Standard Model

In 2019, the DESY CMS group found an excess in data from Higgs-boson searches in top-quark pair ($t\bar{t}$) final states that could be a hint for the presence of a CP-odd Higgs boson at a mass of about 400 GeV. In earlier analyses, excesses were observed at about 96 GeV at the CMS experiment in di-photon events and at CERN's former LEP collider in bottom-quark pair production. In a joint effort together with members of the $t\bar{t}$ analysis team of the CMS search, members of the DESY theory group investigated whether the excesses can be accommodated in models with an extended Higgs sector compared to the one of the Standard Model (SM), while being in agreement with all other experimental constraints.

The discovery of a Higgs boson in 2012 at the LHC was a huge success for particle physics and an important milestone in understanding the nature of electroweak symmetry breaking. At the same time, the discovery raised many questions. Does the new particle behave according to the predictions of the SM? Is it the only elementary particle with vanishing spin?

Exploring the data recorded in 2016 at the CMS experiment, the DESY CMS group tried to answer such questions by searching for new heavy Higgs bosons decaying into pairs of top quarks ($t\bar{t}$). Studying the $t\bar{t}$ mass distribution and a helicity angle that depends on the spin of the heavy Higgs boson, the team found a deviation with respect to the SM predictions that is compatible with a new CP-odd Higgs boson with a mass of about 400 GeV (Fig. 1, left), where the local significance of the excess amounts to 3.5 standard deviations [1]. In addition, excesses were observed at a mass of about 96 GeV at CMS in di-photon events and at the LEP collider in bottom-quark pair production ($b\bar{b}$).

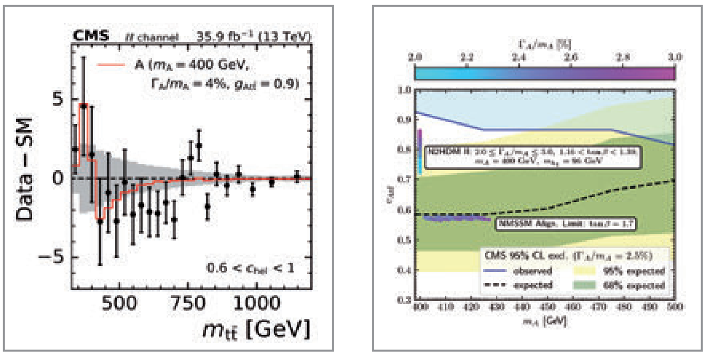

Figure 1

Left: Impact of an additional Higgs on the top-quark pair mass distribution.
Right: N2HDM and NMSSM parameter space that can explain the excess.

Each of these excesses alone is not yet significant enough for regarding it as a discovery. However, if several of the excesses could be interpreted simultaneously in an ultraviolet-complete model, where the biggest challenge is to ensure that one is in agreement with the huge amount of experimental constraints from other collider measurements, the hypothesis of a particle origin of the excesses would be very compelling.

To this end, DESY theorists joined forces with DESY experimentalists from the CMS group to discuss two popular models that feature non-minimal Higgs sectors and thus additional neutral and charged Higgs bosons [2]: the Next-to-Minimal Supersymmetric Standard Model (NMSSM) and the Next-to Two Higgs Doublet Model (N2HDM). Interestingly, they found that both models can describe the CMS $t\bar{t}$ excess with a CP-odd Higgs boson at 400 GeV, while, at the same time, one or both excesses at 96 GeV can be accounted for by the presence of a new Higgs boson with reduced couplings to the SM particles. The results with regard to the $t\bar{t}$ excess of both scenarios are summarised in Fig. 1, right. The DESY scientists are eagerly awaiting updated results in the di-top and di-photon final states, including the full LHC Run 2 data set, to shed more light on the origin of the excesses.

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References:

[1] CMS Collaboration, JHEP 04, 171 (2020)
[2] T. Biekötter, A. Grohsjean, S. Heinemeyer, C. Schwanenberger, G. Weiglein, Eur. Phys. J. C 82, 178 (2022)

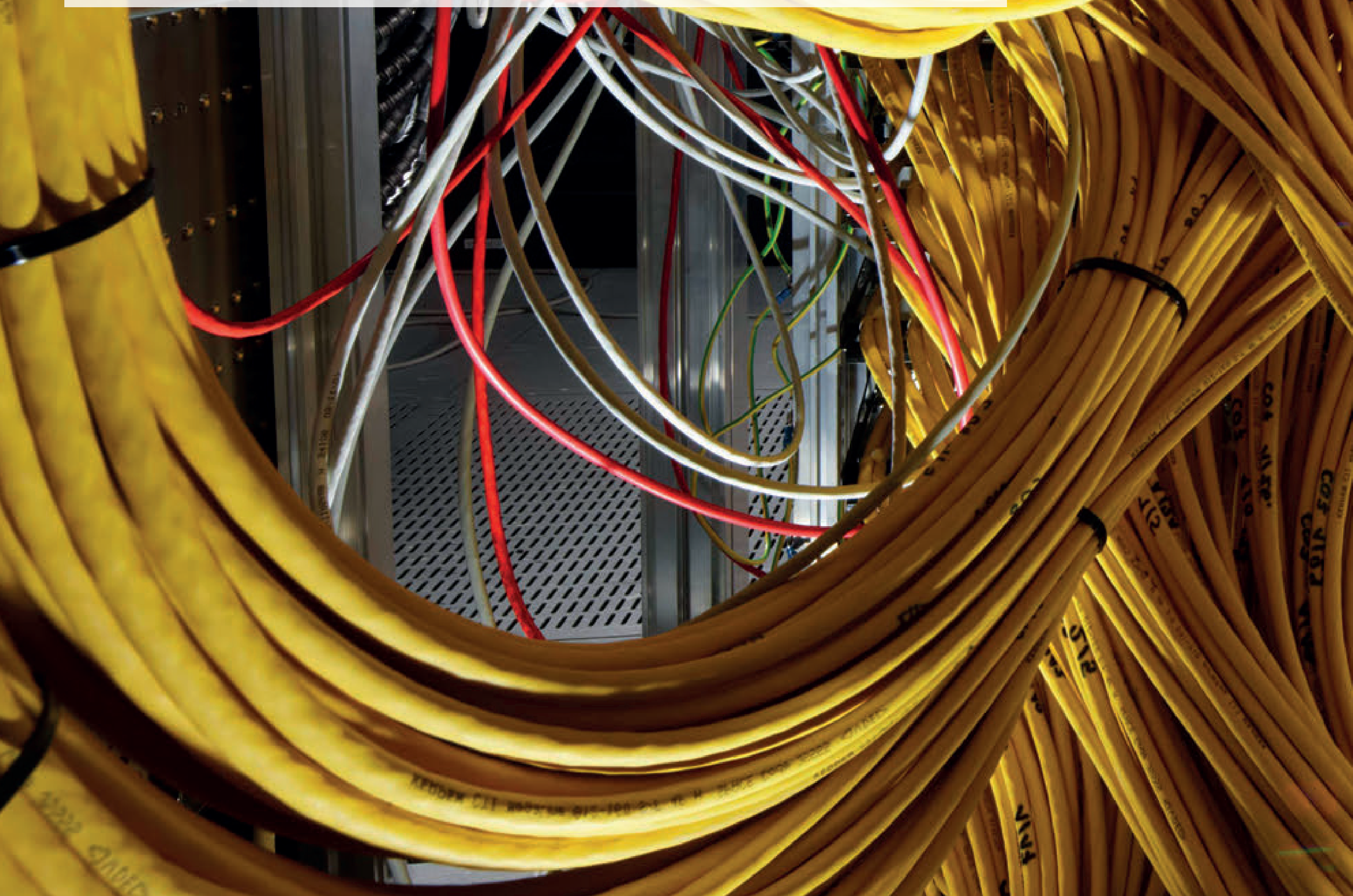
Projects and infrastructure

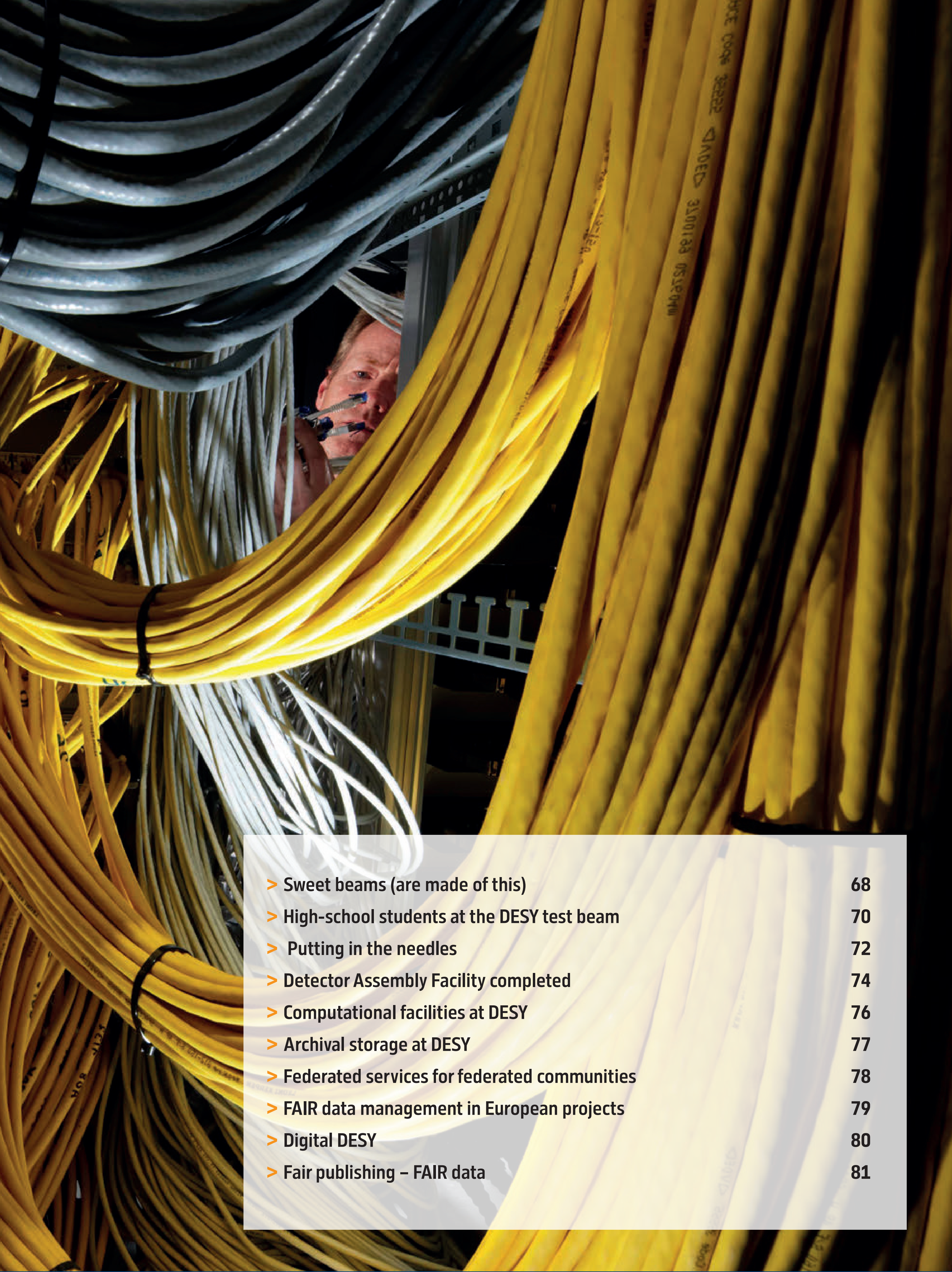
The experimental and theoretical research activities at DESY would not be possible without the contributions and support from numerous groups and people. One important service offered by DESY is its Test Beam Facility at the DESY II synchrotron. Scientists from all over the world are using the facility to subject newly developed detector components, e.g. for the International Linear Collider (ILC) or the LHC upgrades, to tests with electron or positron beams (p. 68). In 2021, the group also successfully hosted the Beamline for Schools competition again (p. 70).

Just as essential are the DESY groups that design and manufacture important components for particle physics detectors. Important activities here are tracker development and testing (p. 72) and the Detector Assembly Facility (p. 74).

Computing too is a crucial ingredient. The DESY IT group is constantly striving to improve its services for all users and needs, for example uniting the capabilities of the Helmholtz community (p. 76), efficiently archiving data (p. 77), providing services in a federated system (p. 78), or fostering an open data management process (p. 79).

Meanwhile, the DESY library group has been working to facilitate all processes related to publishing and the management of publication databases (p. 80 and 81).





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Sweet beams (are made of this)

DESY II test beam keeps its shutters open despite the pandemic

DESY operates the DESY II Test Beam Facility for R&D projects from the global particle detector community and beyond. In 2021, the facility started running only in March due to the COVID-19 lockdown regulations in place in Germany at the time. From then on, it was successfully operated in a COVID-19-safe mode until the December shutdown. Despite difficulties caused by travel restrictions and team size limitations, way over 300 users came in 2021. The world-class infrastructures at DESY, such as the EUDET-type pixel beam telescopes or the large-bore magnets, continued to be in strong demand. The facility also hosted the Beamline for Schools competition again in close collaboration with CERN.

The DESY II Test Beam Facility

The DESY II Test Beam Facility uses the DESY II synchrotron for beam generation and offers three beamlines located in Hall 2 on the DESY campus in Hamburg. The beamlines can be individually controlled by the user groups and provide electron or positron beams in the energy range from 1 to 6 GeV. The test beam team constantly strives to keep the facility a world-class venue for detector R&D.

2021 – Operating in the second year of the pandemic

During the winter shutdown 2020/21, the test beam team was very busy getting the facility ready for the 2021 run. Major upgrades went ahead despite the difficulties due to overall lockdown in Hamburg, which also delayed the planned start of user operation from early February to 15 March.

Together with the DESY health and safety experts, an updated strategy was developed to allow COVID-19-safe user operation in view of new coronavirus variants. In coordination with the photon science beamline teams at DESY, the strategy was adjusted a few times to react to the overall situation, thus successfully enabling operation throughout the year. Thanks to everyone working together, much-needed test beam time could be provided for many groups in a safe way.

Despite the circumstances, 2021 was a very successful run with 316 users from 16 countries. Mainly due to travel restrictions, this time over two thirds of the users came from Germany. Again, the biggest fraction of the users had an LHC background, but for the first time their share fell below 50%. Although this decrease was partly due to cancelations because of travel restrictions or the non-availability of components, it also underlines the move towards production for the HL-LHC upgrades. Generic detector R&D projects were on the rise, exploring new sensors and ideas for the next generation of experiments. Regarding the choice of technology, monolithic active pixel sensors are considered by many groups as the technology of choice for the next generation of tracking detectors.

With the start of the AIDAinnova project, work has commenced to upgrade the beam telescopes with new sensors and better timing capabilities. As a stepping stone, the TelePix project, funded by the cluster of excellence Quantum Universe, is developing a sensor with nanosecond hit timing and a very flexible region-of-interest trigger. In addition, the test beam facility also supported the DESY on-site particle physics programme with test beam campaigns studying sensor technologies for LUXE and testing mechanics for BabyIAXO in the large-bore dipole magnet in Area T21.

Finally, the Beamline for Schools competition in collaboration with CERN was hosted for the third time, with one student group from Italy and one from Mexico performing their experiments at the DESY test beam.

Highlights

New primary target stations

The test beams are generated by inserting 7 μm thin carbon fibres into the DESY II primary beam. Given the high

Figure 1

View of the DESY II Test Beam Facility in Hall 2 with the user huts (blue) and the beamlines (green). The new User Hut 23 is visible on the right beam intensity, the carbon fibres have a limited lifetime. The target stations that were installed in 2012 required a quarter of the accelerator ring vacuum to be vented in order to replace the revolver with six mounted fibres. Replacing targets thus needed at least 60 hours and was only possible during a shutdown.

Together with experts from the accelerator division, new target stations were developed, which require only the station itself to be vented and make swapping the targets an operation of a few hours. Now, ten fibres are mounted on a "target harp". The new stations were successfully installed in the winter shutdown 2020/21 and performed extremely well throughout 2021.

Hut 23 – New working space for test beam users

Even before the pandemic, space for users was tight in the measurement huts. With the COVID-19-related limitations on room occupancy, this became a real issue in 2020 even with smaller team sizes. Therefore, a new user hut of nearly 40 m^2 was built, providing additional work space since mid-2021, including a corner for video conferencing (Fig. 1).

The R-Weg – Extracting the primary beam from DESY II

A long-term project came to completion in the winter shutdown 2020/21. The R-Weg (for "Roter Weg", "red path") was originally used as a transfer line to the DORIS accelerator and shut down together with DORIS in 2013. For several years, it was discussed to use this beamline to extract the primary beam from DESY II in order to provide a high-intensity test beam for specific user needs. The R-Weg allows up to 10^{10} electrons with an energy of up to 6.3 GeV to be extracted at a repetition rate of 12.5 Hz. Besides providing – from a test beam perspective – an infinite number of tracks, this beam can also be used to study radiation damage effects.

After the former beamline and installations were completely dismantled and the tunnel was emptied, an experimental area was set up inside the R-Weg for first expert experiments. A new interlock system was installed and new instrumentation for beam diagnostics and radiation safety completed the setup. The commissioning of the new beamline started after the summer shutdown 2021, and beam intensity and quality have been steadily improved since then.

T2K

Thanks to the PCMAG superconducting magnet, with a diameter of 72 cm and a magnetic field of up to 1 T, the DESY II Test Beam Facility has frequently been used for detector tests requiring a solenoidal magnetic field. In May 2019 already, the magnet was used to test a small prototype chamber of the new high-angle time projection chambers (TPCs) for the upgrade of the near detector of the T2K neutrino long-baseline experiment in Japan. The upgraded T2K experiment is planned to start in 2023.

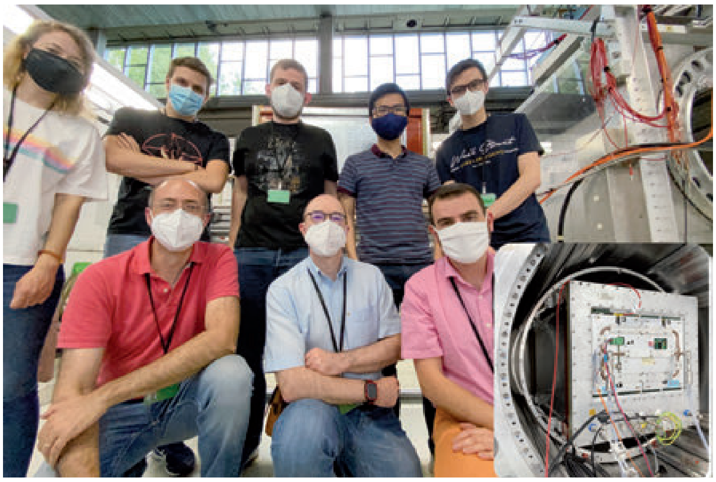

Figure 2

T2K on-site test beam team, with the detector under test in the inset

A second test beam campaign with the final readout detector, called ERAM (encapsulated resistive anode micromegas), the front-end electronics and the data acquisition took place in June 2021 (Fig. 2). The main goal was to finalise the design of the high-angle TPC subcomponents for the upcoming production. To this end, the performance in terms of spatial and energy resolution in a magnetic field of 0.2 T was studied in detail. The two-week campaign was very successful and generated a copious harvest of high-quality data, which is still being analysed.

Outlook for 2022 and beyond

The winter shutdown 2021/22 will be very short, with DESY II back at the end of January and user operation resuming on 7 February. A major focus will be the future of the test beam facility in light of the major overhaul of the accelerator complex for the PETRA IV upgrade. This is an ongoing discussion that will certainly continue for the next few years.

Summary

In retrospect, 2021 was almost as challenging for the DESY II Test Beam Facility as 2020, and everybody is now looking forward to slowly coming back to the usual mode of operation. Despite the difficulties during the pandemic, a lot of progress was made, new infrastructures were put into operation, and the facility kept delivering beam to users. The success of the test beam facility would not have been possible without the support from many individuals and groups from the DESY particle physics and accelerator divisions. We would like to take this opportunity to thank everybody involved.

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High-school students at the DESY test beam

CERN's Beamline for Schools competition: Successful third round during the pandemic

In autumn 2021, CERN's Beamline for Schools competition took place at the DESY II Test Beam Facility for the third time. For the first time in the history of Beamline for Schools, one of the two winning teams came from Mexico. The second winning team originated from Italy. Unlike in 2020, both teams were able to travel to DESY to perform their experiments. Despite all the challenges that had to be overcome, the eighth edition of the competition once again turned out to be a very successful event.

International science competition

In the Beamline for Schools (BL4S) competition, teams of high-school students are asked to phrase their own research questions and design fixed-target experiments to investigate these questions. The constraints: The experiment has to be devised in such a way that it can be performed at a test beam facility within one week of beamtime, and it should make use of the detectors and equipment available to the project. The competition is open worldwide and has received contributions by teams from more than 90 countries over the past eight years. In 2021 alone, 289 experiment proposals were submitted from 57 different countries. The first prize for two winning teams per year is a two-week visit to CERN or, in 2019, 2020 and 2021, to DESY to conduct their own proposed experiments guided by scientists.

The competition has been managed by CERN since 2014, where it started as a highlight of CERN's 60th anniversary activities. Until 2018, the experiments were performed at the PS test beams at CERN. Due to the long shutdown of the CERN accelerator complex, the competition had to evolve: DESY premiered as host in 2019 and committed to receive the winning teams and experiments again in 2020 and 2021, with great interest to continue this collaboration in the future.

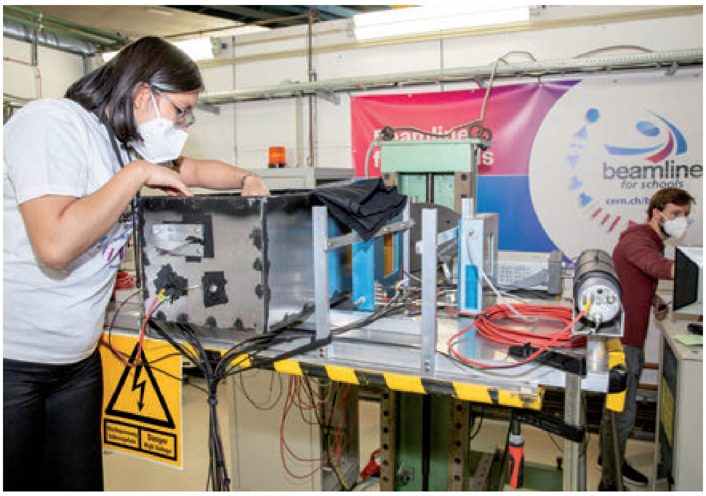

Figure 1

Assembling the setup of team Teomiztli at Beamline 21 at the DESY II Test Beam Facility

Winning teams of BL4S 2021

In 2021, selecting the winning teams became even harder. With almost 300 submitted proposals from 57 countries and more than 2000 participating students, the selection committee took their time and evaluated all the proposals very carefully. After two challenging months, 23 teams were shortlisted and 10 teams received a special mention, all of them winning attractive prizes. Two teams of high-school students, one from Liceo Scientifico Statale "A. Scacchi" in Bari, Italy, and the other from Esculea Nacional Preparatoria "Plantel 2" in Mexico City, Mexico, won the competition and got to spend two weeks at DESY in September 2021.

The students' experiments

The winners of the BL4S 2021 proposed two challenging but exciting experiments.

The Italian team EXTRA investigated the transition radiation effect, where X-ray photons are produced when

Figure 2
On-site participants of the BL4S 2021 VIP day at DESY

a beam of high-energy electrons crosses the interface between materials with different optical properties. To study this phenomenon, the students had to discriminate the signals produced by the particles in the beam from those produced by the X-ray photons.

The experiment proposed by the Mexican team Teomiztli focused on Cherenkov radiation: the production of electromagnetic radiation when high-energy particles travel through certain materials. The goal of the Mexican students was to compare the production of Cherenkov radiation in different materials, with a possible application in the development of particle detectors in mind (Fig. 1).

BL4S and corona – second edition

With the overall pandemic situation improving in summer 2021, the two winning teams prepared themselves for their stay at DESY. In particular, they were all vaccinated against COVID-19 to facilitate travel and protect themselves and others.

Finally, on 8 September 2021, the Italian and Mexican students arrived at DESY, accompanied by their teachers. After a few days to familiarise themselves with the research centre and visit the city, they started their experiments. During their stay, the teams alternated data-taking shifts at the test beam, visits of the centre and data analysis sessions under the supervision of a group of volunteers, mainly PhD students and post-docs from DESY. Despite the pandemic regulations, the students managed to complete their experiment plan and make the most of the experience.

The VIP day in 2021 was particularly successful. The event was organised in a hybrid format with some people on site at DESY (Fig. 2), some people on site at CERN and connected to the DESY main auditorium, and others connected remotely. Overall, more than 100 people attended the event, and the questions and answers session at the end was particularly lively.

BL4S 2022

The next edition of the competition in 2022 will be hosted at CERN again. Two teams will be selected and have the possibility to run their experiments at one of the beamlines of the PS accelerator. Nevertheless, the collaboration with DESY will not be over, and a third team might have the opportunity to conduct its experiment in Hamburg. With more and more teams taking part in the competition and with the experience of the past three editions, the collaboration between CERN and DESY will be a strong asset for the future of the BL4S competition.

Acknowledgements

BL4S is an education and outreach project funded by the CERN & Society Foundation and supported by individual donors, foundations and companies. In addition, BL4S at DESY is supported by a large number of local groups. We would like to take this opportunity to thank the volunteers, colleagues and groups involved for their invaluable support.

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Putting in the needles

An elegant test tool for ATLAS EoS production

For the high-luminosity upgrade of the LHC, the ATLAS inner tracker (ITk) will be upgraded with a new silicon tracker to achieve the physics goals planned for the experiment. One of the key electronic components inside the detector is the end-of-substructure (EoS) board, which serves as a high-speed interface between the on-detector modules and the off-detector components. This printed circuit board (PCB) has been designed at DESY and will be produced and tested there as well. The performance of the digital signal paths on the EoS board is particularly challenging to verify – a needle probe test adapter is the solution of choice.

Challenging electronics design and testing

One essential tool for leading-edge research is the electronic equipment in an experiment. With a broad selection of analogue and digital devices, it is possible to collect and process the interesting data from the experiment. History has shown that major improvements of these electronic components have directly affected measurement results and accelerated the gain in knowledge. In combination with the increased performance of integrated circuits, miniaturisation, in particular, has had a strong influence in this development.

For most applications, commercial components can be used in the experimental setup. For some experiments, however, commercial components are not suitable because of hostile environmental conditions, such as radiation, temperature or pressure at the installation site. Another simple reason could be space or weight constrains. Under these circumstances, new, dedicated electronic components and PCBs have to be developed and designed to meet the requirements of the installation site. Given the space constraints on these tightly packed PCBs, which prevent the use of test connectors, a smarter way to verify the performance of the electronics after production is needed.

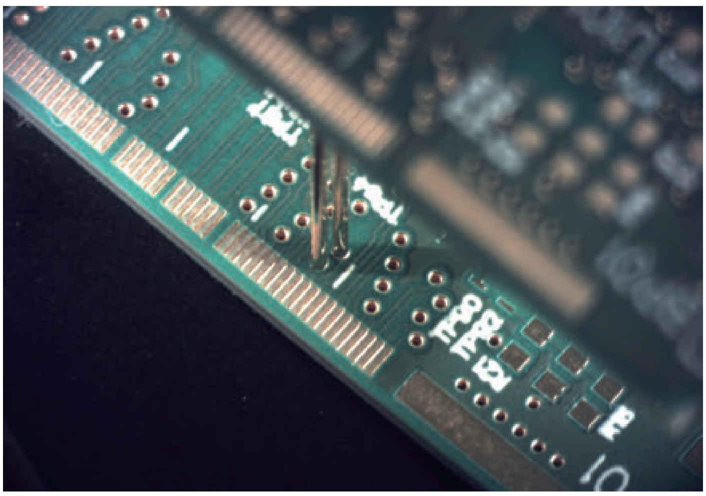

Figure 1

Checking the ATLAS EoS with a needle probe test adapter

The environmental conditions in the ATLAS experiment require an electronics design with radiation-resistant materials and limited size. Owing to the complex structure of the tracker, six different types of EoS boards had to be designed. The quantities required varied between 150 and up to 400 boards per type. During the development phase, the question how to test all the produced boards before they were installed in the detector was always present, as the boards are inaccessible once they have been installed inside ATLAS. Driven by these high quality assurance / quality control demands, one problem was to verify the performance of the entire digital signal paths on the EoS board with a complete bit error test (BERT). For this purpose, all the digital lines had to be concurrently driven with an independent pseudorandom binary sequence signal (PRBS) at speeds up to 640 Mbit/s.

Usually, a simple connector is used to connect the signal lines with the external test equipment. Unfortunately, these lines are terminated at the PCB edge with bond pads that clearly exclude the use of connectors. In this situation, a needle probe test adapter is a smart way to solve the problem.

For such a test, test points for needles have to be placed very close to the bond pads in order to reduce the effect of an open line on these fast signal traces. This gives the opportunity to check nearly all sections of the signal lines. These test points have a nominal very small distance of

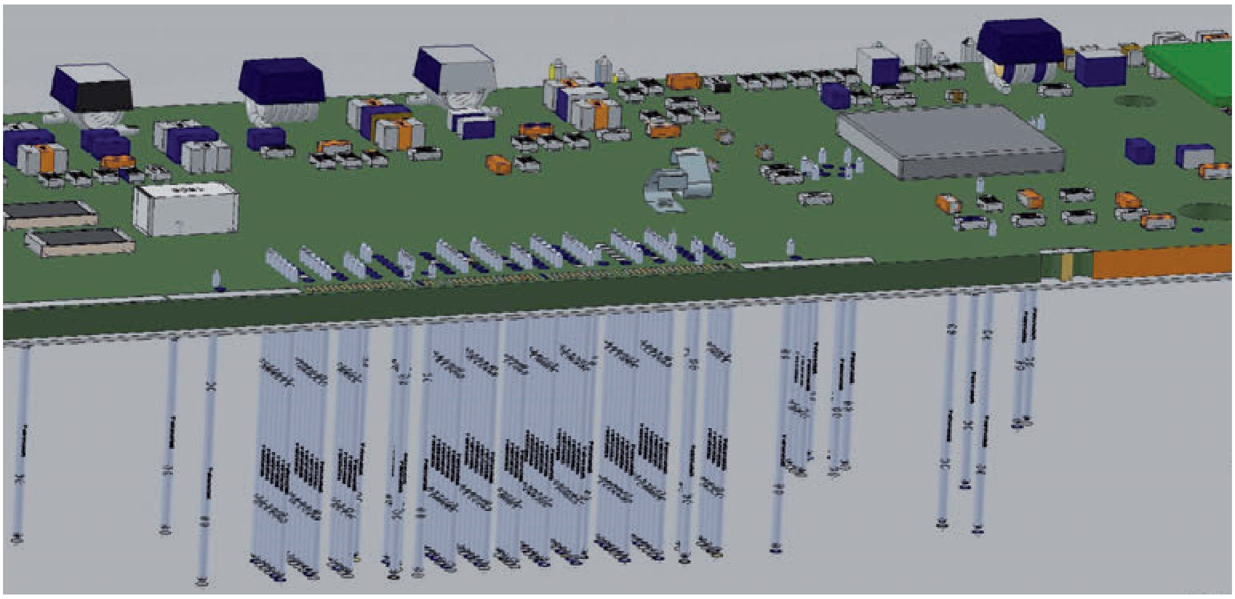

Figure 2
Placement of the needles

700 µm on the EoS board. Around 140 needles with a diameter of just 510 µm are used to connect all the interesting signals, even the 28 fast differential lines with data rates of 640 Mbit/s.

The counterpart for the needles is a specially designed PCB inside the test adapter. Installed directly under the EoS board, it acts as the "a-glue" between the device under test and the external measurement equipment, with parallel access to all contactable signals on the EoS board. This feature is also very useful for extended error diagnostics. For the slow analogue and digital signals, some devices such as analogue-to-digital converters, digital-to-analogue converters and multiplexers were placed on this board for test purposes.

Given the small test point distances, the exact positioning of all the components is a formidable mechanical challenge. On top of this, the positioning must be done reliably for a large number of contact cycles ($>10^6$).

Designed for a temperature range down to -40°C, the needle probe test adapter can also be used in a temperature chamber to study the behaviour of the EoS board at different temperatures in order to ensure the performance under these conditions. Several bit error tests demonstrated the reliability of the setup and showed a BERT value of less than 10^{-15}, exceeding the requirements by three orders of magnitude, even for the fast 640 Mbit/s signals guided through the needles.

Beside all the benefits of such a test adapter, a few additional points warrant some attention. Every test adapter is uniquely designed for a single board that has to be tested. This is a time- and cost-intensive development. For instance, when the positions of the assembled components and test points or some mechanical dimensions of the test board change, it may be necessary to develop a new adapter.

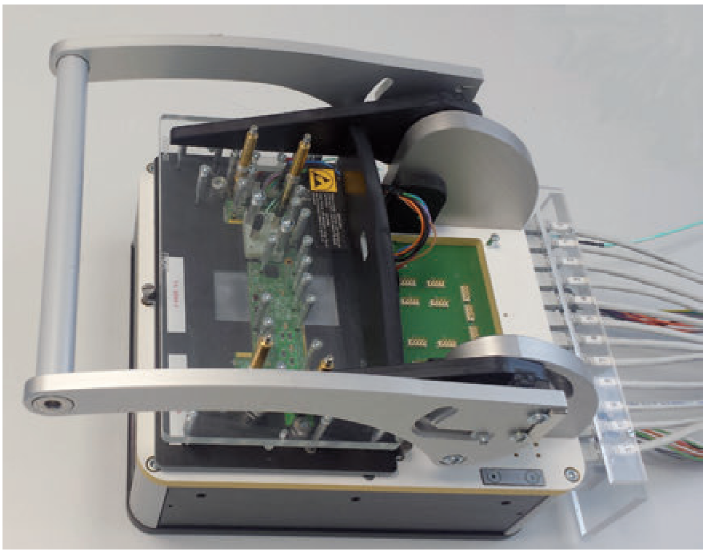

Figure 3
Needle probe test adapter for the EoS board

All in all, however, the application of such a needle probe test adapter offers precise and repeatable access to all interesting signals on a test board in the development and production phase. Especially for tightly packed boards with concurrent signal measurement, such as the EoS board, it is the ideal instrument for testing. A bunch of needles thus enabled us to take the quality control for the ATLAS EoS to the next level.

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Detector Assembly Facility completed

Ready to build the high-precision large-scale silicon detectors for the HL-LHC

For the high-luminosity upgrade of the LHC (HL-LHC), the ATLAS and CMS collaborations are building improved tracking detectors. For both experiments, one end-cap will be constructed at DESY in cooperation with German institutes. The high-precision large-scale detectors made of thousands of silicon sensor modules have to be built in a clean environment to reach the required quality. Large cleanrooms are thus needed to enable the production of the modules and the assembly of the end-caps. The corresponding infrastructure, the Detector Assembly Facility (DAF), was realised from 2016 by reusing two existing buildings on the DESY campus. After more than five years of planning, construction and installation, the DAF was successfully commissioned in 2021. The infrastructure is now ready for the series production, which is planned to take place in the coming three years.

The outer tracking detectors of ATLAS and CMS for the HL-LHC [1, 2] are based on silicon sensor modules with an active area of about 10 x 10 cm^2. The modules are arranged in three subdetectors: the barrel, a cylindrical part with several layers around the collision point, and the two end-caps, also made of several layers of disk-like objects, which close the barrel on each side.

One end-cap is composed of roughly 3000 modules and will cover an area of 30 m^2 (ATLAS) and 46 m^2 (CMS) with silicon sensors. DESY has committed to building one end-cap each for ATLAS and CMS. The project has to deal both with small-scale, high-precision silicon sensor structures requiring micrometre-scale precision and with global structures with an overall size of about 3 x 3 m^2. For this purpose, the DAF was built at DESY. It consists of three dedicated cleanrooms adapted to the corresponding requirements. One of the cleanrooms is designed for the very challenging production of the silicon modules and multimodule structures with high precision, while the others are used for assembling, testing and integrating the support structures into the full-scale end-caps while maintaining the needed precision.

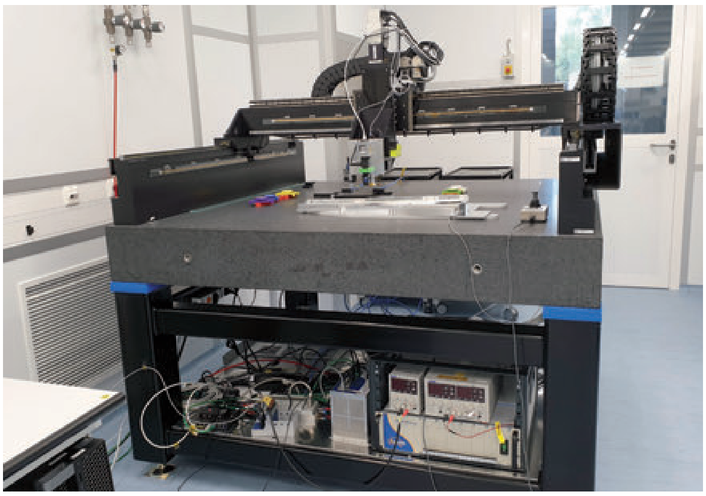

Figure 1

Automated module mounting on the petal structure for ATLAS

Producing silicon sensor modules

The silicon modules made of silicon sensors and readout hybrids are very sophisticated objects that have to undergo several high-precision assembly steps. These production steps require a clean, temperature- and humidity-controlled environment and dedicated infrastructure.

To this end, a cleanroom with Quality Classification 6 according to ISO 14644-1 standards (ISO-6), which corresponds to a maximum of 8320 particles larger than 1 µm per cubic metre of air, has been realised in Building 25c at DESY. The cleanroom has a total area of 250 m^2, which is divided into 20 m^2 of common space and two separate lab spaces for ATLAS and CMS, each with about 115 m^2. A personnel airlock and a material airlock are available for entering the cleanroom or bringing in larger pieces of equipment.

Throughout the cleanroom, outlets for dry and clean pressurised air, nitrogen and vacuum are provided to the users. In the common area, a wet bench with a purified-water outlet and drains for liquid chemicals are available for small-scale cleaning applications. The cleanroom is equipped with specialised equipment to handle specific tasks, such as probe stations, automatic thin-wire bonders, wire bond pull testers and optical inspection equipment. Dedicated robotic systems to automate the critical high-precision assembly steps for the thousands of modules to be built have been developed and produced [3]. Figure 1 shows the automated gantry for module placement of the ATLAS petals.

Assembling 70 m² of silicon sensors

The produced silicon detector modules are mounted onto mechanical structures, and finally both end-caps are assembled. Prior to installation, both the modules and the mechanical structures need to be qualified and hence undergo different tests.

For this, a second cleanroom system with a total area of 750 m² was built in an existing hall on the DESY campus. This cleanroom with less stringent requirements on the particle contamination and hence ISO-7 classification is divided into two individual halls connected by a clean transit area with an airlock to decouple the two areas. Access to the system is provided through a personnel airlock, and a material airlock is available for larger equipment. The environmental conditions are stabilised to 21 ± 0.5°C in temperature and 45 ± 5% in relative humidity.

In both areas, cooling-water outlets are available that allow for an efficient operation of the CO_2 and other cooling plants required for the cold tests. In addition, outlets for nitrogen and dry pressurised air are provided throughout the cleanroom.

The first part of the cleanroom with 290 m² will be used for the integration of the modules onto their mechanical support structure and the subsequent testing at the final operation temperature down to -35°C as well as for the evaluation of some of the local support components.

In addition to commercial equipment, such as a climate chamber, a smart scope and a CO_2 cooling system, several specific automated test and assembly systems were designed and installed, such as an automated infrared scanning system for the CMS half-disk structures (called Dees), a burn-in test system for silicon modules and a robotic production system for the ATLAS petal cores [4]. Figure 2 shows a CMS Dee in the infrared scanning setup used to test the quality of the cooling.

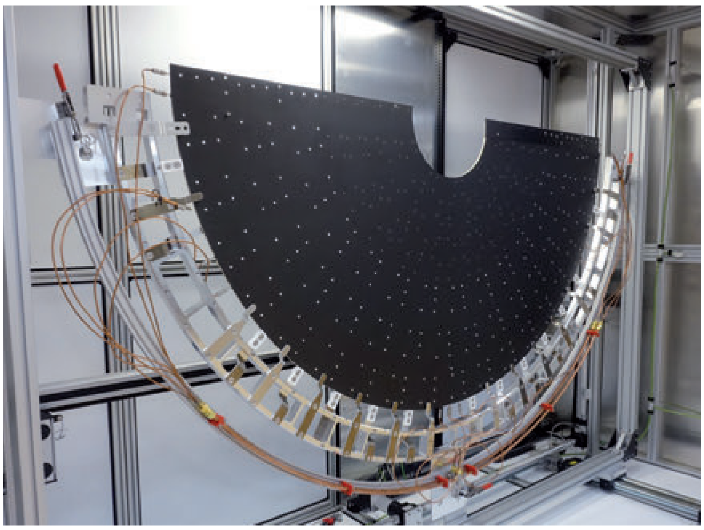

Figure 2

CMS Dee in the infrared scanning system

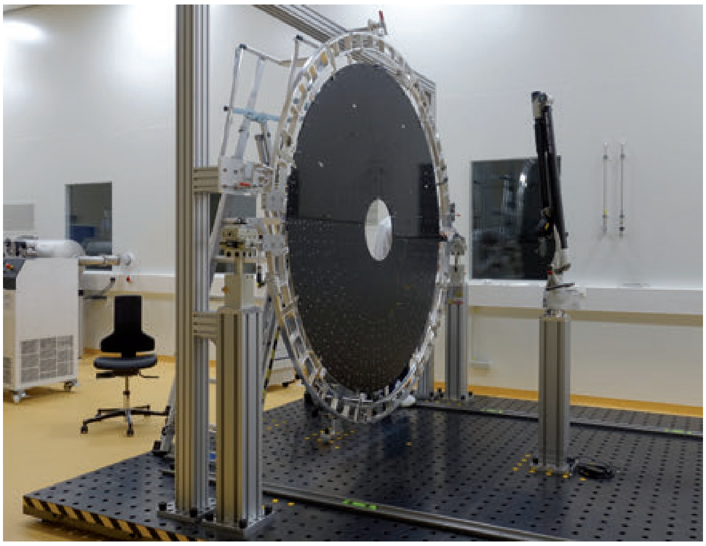

Figure 3

Integration area for the CMS end-cap, with two Dees in the mounting frames

The second part of the cleanroom with about 330 m² and a larger ceiling height of 5 m will be used for the final integration into the end-caps. It will also host the ATLAS end-cap system test setup.

Figure 3 shows the area of the integration hall where the CMS end-cap will be assembled. The first two prototypes of the Dees, which will eventually be equipped with the modules, are installed in a dedicated mounting frame. The integration is done on a high-precision mounting platform of 3.6 x 4.4 m² size to allow the assembly of the CMS end-cap disks with the required accuracy. A high-precision metrology system to monitor the mechanical accuracy and a CO_2 system for system tests are also available.

For ATLAS, an insertion tool for fitting the wedge-shaped petals into the ATLAS end-cap is being installed in the same cleanroom, as well as an additional CO_2 cooling system for system and disk sector tests.

The commissioning of all the cleanrooms and the installed equipment was successfully completed in 2021 with the production of the first fully functional module prototypes and the first mechanical structures. Current planning foresees that the two end-caps for ATLAS and CMS will be built and tested in the DAF infrastructure by the end of 2025 before being delivered to CERN for final installation in the full detector system.

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References:

[1] Technical Design Report for the ATLAS Inner Tracker Strip Detector, CERN-LH CC-2017-005
[2] The Phase-2 Upgrade of the CMS Tracker, CERN-LHCC-2017-009
[3] CMS tracker upgrade, this report, page 25
[4] ATLAS tracker upgrade, this report, page 30

Computational facilities at DESY

News from the IDAF

A pivotal element in science today is a first-class computational platform to accompany first-class experimental facilities. DESY operates both kinds of facilities. This article summarises the status of the Interdisciplinary Data and Analysis Facility (IDAF) at DESY, which came to life with the fourth Helmholtz programme-oriented funding period (PoF IV), extending DESY's Tier-2 facility for (mainly) high-energy physics with the Maxwell HPC system, DESY's computing facility for photon science and accelerator R&D and operation.

Starting with PoF IV in 2021, the IDAF officially came to life. Its founding elements are not new, however: the Tier-2 facility, the National Analysis Facility (NAF) and the Maxwell high-performance computing (HPC) system at DESY. For technical, operational and political reasons, these systems had grown separately. The NAF and Grid systems were already merged in the past, which brought many synergies enabling better service to users.

With the start of the IDAF, it is time to review the larger picture. First, computing for photon science and accelerator R&D and operation has caught up with, if not outpaced, computing for high-energy physics. Second, HPC computing and machine learning infrastructure are becoming essential tools in the DESY computing portfolio. Third, the data deluge in all of the science areas at DESY necessitates further investments. Last but not least, a uniform user experience over all parts of the facility is key to its acceptance and success and must be a guiding factor when leveraging the IDAF.

Data is the pivotal part of all DESY science, and scientific output increases with ease of access. In 2021, the cluster storage systems on the NAF and the user home directories on Maxwell were due to be replaced. The new storage system has a central place offering access to all nodes in the NAF and Maxwell at the respective highest possible speed. This approach will act as a blueprint for future storage system configurations to improve user experience and move towards a fully integrated system.

Figure 1
New tape robot in the computing centre at DESY in Hamburg

For 2021 and 2022, the groups in the Helmholtz topic Accelerator R&D (ARD) and the teams operating the FLASH and European XFEL accelerators requested considerable increases in their computing share. In a similar approach to the cluster storage, DESY IT implemented a setup that enables the IDAF to offer unified access to the data through various means.

In 2021, DESY also replaced its tape library on which all raw data collected by the local experiments is stored. The migration of the existing data is still ongoing; data taken in 2021 have already been stored in the new library. This migration will continue well into 2022. In line with the procurement, the software that manages the data stored in the library was revised as well. The existing solution will be replaced by the CERN Tape Archive (CTA) software, which will see widespread use in the future at sites storing LHC raw data. DESY is active in developing software that will allow the CTA software to operate smoothly with the existing IDAF storage. The operation and the organisation of new purchases were challenging in 2021 due to the pandemic and the sparse availability of components. Nevertheless, we managed to minimise the impact on users. All in all, the IDAF provides 60 000 physical CPU cores and 500 GPUs on 1800 compute nodes and has access to 85 PB of dCache data.

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References:
[1] https://grid.desy.de/
[2] https://naf.desy.de/
[3] https://maxwell.desy.de/

Archival storage at DESY

dCache and tape libraries for modern storage systems

The ever-increasing amount of data produced by modern scientific facilities, such as the European XFEL or the LHC, puts high pressure on the data management infrastructure at the laboratories involved. The challenges that have to be addressed span the full data life cycle, from ingest through efficient data analysis to long-term preservation. The latter typically relies on magnetic tape media, which – in combination with disk storage – covers the data management requirements. The DESY IT group uses dCache, a storage system developed at DESY in collaboration with Fermilab and the Nordic eInfrastructure Collaboration (NeIC), to manage large numbers of disk servers and transparent data migration to and from archival storage.

Archival storage evolution

Though, today, large hard-disk-based systems are cost-, space- and volume-effective, magnetic tapes are still the best option for long-term data archival: Tape cartridges don't require electric power when not used, can store up to 20 TB of uncompressed data and are designed for 15–30 years of archival storage.

When streaming, a modern tape drive provides up to 400 MB/s. However, positioning time is on average about 50 s. Moreover, magnetic tapes don't support concurrency, meaning that only one file can be read or written at a time. To achieve maximum efficiency of the available tape resources, deep integration of all hardware and software components is required.

Since the early 1990s, DESY IT has been relying on the Open Storage Manager (OSM) software to access data on tapes. Although over 80% of the original code base has been updated, the scaling capabilities included in the original design are no longer sufficient today. Moreover, the commercial OSM software licence does not allow DESY IT to share its changes with the broader scientific community.

The CERN Tape Archive (CTA) is an open-source tape management software developed by CERN IT to meet the requirements of LHC Run 3 and the HL-LHC. For seamless integration with CTA, the dCache developers at DESY have implemented a CTA-specific driver, which provides efficient integration of both systems.

Current status and outlook

The dCache+CTA system has been installed at DESY and is being tested intensively with a production-like load. The DESY IT group is confident that the dCache+CTA combination will address the data archival requirements of high-energy physics, photon science and European XFEL at DESY for the next decades. We hope that other labs that use dCache and tape libraries or plan to install one will benefit from our work. For this reason, all our activities are documented and shared with the dCache community.

Figure 1

The new tape library at DESY

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References:

[1] T. Mkrtchyan, K. Chitrapu, V. Garonne, D. Litvintsev, S. Meyer, P. Millar, L. Morschel, A. Rossi and M. Sahakyan, EPJ Web of Conferences 251, 02010 (2021)

[2] E. Cano, V. Bahyl, C. Caffy, G. Cancio, M. Davis, O. Keeble, V. Kotlyar, J. Leduc and S. Murray, EPJ Web of Conferences 251, 02037 (2021)

Federated services for federated communities

Scientific collaboration across institutional borders

In 2021, the DESY IT group extended the existing identity provider (IdP) service to meet the demand for OpenIDConnect (OIDC)-based authentication and authorisation – an industry standard also used by large technology firms, such as Google, Microsoft or PayPal. The use case for these services is found in areas where researchers from different institutions collaborate while using services hosted in different centres. With OIDC, they are able to securely access these services with the user names and passwords from their home institutions.

Federated identities

In today's scientific communities, many people from many different institutions are working together on research and development. In the past, all people using applications or computing resources needed accounts and passwords in all the institutions where they were using these services.

As this often created issues with forgotten user names, passwords, expiries and so forth, efforts were made to create so-called federations, which are virtual organisations (VOs) linked by mutual trust relationships. In simpler terms, one organisation trusts that another organisation will manage their users according to common rules. Having this assurance, the first organisation will allow users from the second organisation to access its resources.

Federated services

While trialling these setups, it became clear that it would be helpful for service providers to not only have confirmation of a user's identity, but also receive hints on the user's VO group memberships and allowances to use certain resources (assertions) in a federation. The OAuth2 [1] standard, which is used by the OpenIDConnect scheme, offers these features. A generalised overview is depicted in Fig. 1.

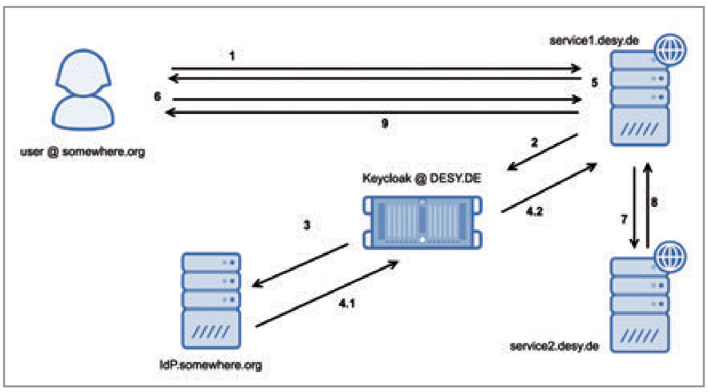

Figure 1

General overview: information flow in federated services

As a second benefit, OAuth2 also allows so-called tokens to be issued that a service can use to obtain access to a third-party service on behalf of the end user.

This entire complex infrastructure allows researchers and developers to interact in their own community using services at any of the member institutions, while only having to use their home institution credentials.

Implementation at DESY

DESY IT decided to implement this functionality on the basis of Keycloak [2], a proxy service that takes care of incoming authentication requests and forwards user IDs and assertion information to the DESY services. At DESY, Keycloak has been extended to communicate with local identity and access management systems to instantiate local accounts or link existing local accounts to the incoming federated identities.

The system is already in operation with several services, e.g. HIFIS Sync&Share, dCache storage for Helmholtz Imaging and some collaborative tools. Work is ongoing to include more services and connect new communities. In addition, DESY IT is investigating the use of multifactor authentication with Keycloak to reduce the impact of credential theft (e.g. by phishing).

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References:

[1] https://openid.net/connect/
[2] https://www.keycloak.org/

FAIR data management in European projects

A win-win adventure

Open science in European research crystallises around the European Open Science Cloud (EOSC), which has been supported by the European Commission for more than 12 years. DESY, as a valued expert in data management and analysis, fosters the implementation of the FAIR (findable, accessible, interoperable and reusable) data principles, a prerequisite for open science, both in photon science and in high-energy physics. The DESY IT group is building on its long experience in big-data management, gained in particular through its involvement in the Worldwide LHC Computing Grid (WLCG), and extending this through its continued participation in the co-creation of the EOSC. In this way, the group is developing its competences in applying the FAIR principles to all the data produced or handled at DESY.

Figure 1
FAIR data life cycle model

DESY in EOSC and NFDI

The EOSC association and the German National Research Data Infrastructure (NFDI) were both created recently to steer the initiatives co-creating an environment for open science across disciplines at the European and German level, respectively. It was important for DESY to be involved, and today, the research centre is not only a member of both associations, but also participating in – even coordinating, in the case of ExPaNDS – several important projects for FAIR data management:

- In photon science: ExPaNDS, PaNOSC and DAPHNE4NFDI,
- In particle physics, nuclear physics and astronomy: ESCAPE and PUNCH4NFDI.

FAIR data for photon science

Automatically minting DOIs for data produced at the DESY facilities and making it easier to record good metadata and to find relevant data produced by others are some of the main outcomes DESY aims to achieve in the EOSC Photon and Neutron Data Service (ExPaNDS). FAIR and open science is a topic that concerns data management and computing experts, librarians and instrument scientists. This is why the project was established with involvement of both the Research and Innovation in Computing (RIC) group of DESY IT and the Scientific Computing (SC) group of the DESY photon science division.

Thanks to projects like this, DESY brings its data, analysis software and know-how in big-data management to the EOSC and benefits in return from the experience of experts from the wider photon and neutron science community in FAIR data practices and standardisation.

European data lake for high-energy physics and astronomy

The European Science Cluster of Astronomy & Particle Physics (ESCAPE) European Strategy Forum on Research Infrastructures (ESFRI) cluster project is working on implementing a particular aspect of FAIR data by demonstrating the feasibility of the data lake concept for its diverse set of communities. This concept allows research institutes to provide federated storage capacity for collaborations in an easy and transparent fashion, with dynamic data placement policies ensuring the desired durability. Such powerful data management underpins the ability for these communities to offer FAIR data.

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Digital DESY

Approval of publications

Publications are the currency of scientific research and, according to the DESY Statutes [1], all scientific results of work carried out at DESY must be published or otherwise made available to the general public. Publications by DESY scientists are of outstanding quality and highly visible. The approval process for scientific publications is part of the quality assurance process. This used to be paper-based, but has been transformed in 2021 into a full electronic workflow.

Approval process

For several decades, the DESY library has been an integral part of the publication process. It collects and indexes all DESY and user publications in the DESY Publication Database (PubDB). The approval process is laid out in the DESY publication rules [2]. According to these rules, all external publications (e.g. journal publications, DESY reports, etc.) need approval, and only after the approval request has been granted is the submission of a manuscript allowed.

The electronic workflow that was implemented by the library starts with a preliminary entry in the DESY PubDB.

In the approval form (Fig. 1), the users document with their electronic signature that:

- An internal review was done,
- The authors' affiliations are correctly stated,
- All authors agree to open-access publishing if permitted by copyright,
- The primary scientific data on which the publication is based is treated according to the rules of good scientific practice [3].

The approvers give their consent by signing electronically as well. The users can see the status of the approval process at all stages on their dashboard (Fig. 2).

After publication, the users complete the entry, and the record is further processed with the well-established standard repository workflow.

The implementation of the approval process within the repository avoids redundant data acquisition and allows an affiliation check by the library, which ensures better visibility and accountability of publications for DESY. The electronic approval process is much more transparent for users and approvers than the paper version. The library is involved at an early stage and can support authors better, for example on copyright and publishing questions.

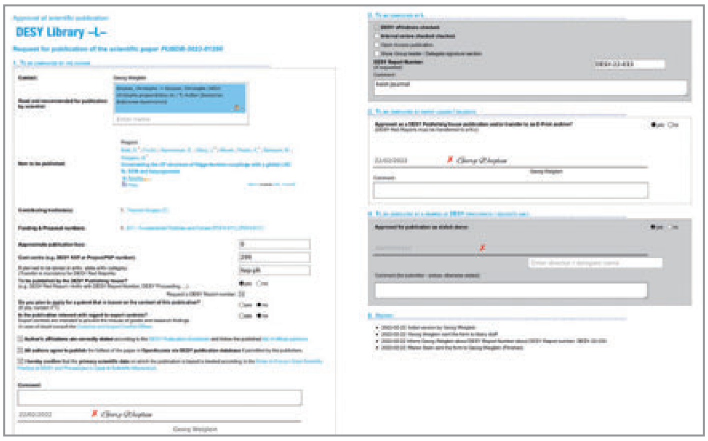

Figure 1

Approval form for the new electronic publication approval workflow

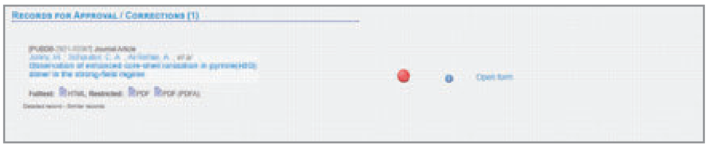

Figure 2

User dashboard

The workflow furthermore ensures that DESY has full-texts for all of its publications centrally archived, and the library can amend the documentation needed for the publication funding provided by the German Research Foundation (DFG, see next page). In addition, the workflow is flexible enough to fit all the different DESY research areas.

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References:

[1] DESY Statutes (in German), https://www.desy.de/ueber_desy/satzung/index_ger.html

[2] Good scientific practice at DESY, https://www.desy.de/administration/rules_and_standards/index_eng.html

Fair publishing – FAIR data

DFG-supported punch lines in the DESY library

In 2022, the DESY library and documentation group will introduce three novelties supported by the German Research Foundation (DFG): open-access advancement, open publication costs and open research data infrastructure, all under the premise of fairness as a fundamental scientific principle.

Open-access publication costs

In the future, open-access publishing will be further emphasised, rewarded and financially supported. For the period from 2022 to 2024, the DFG will provide DESY researchers with partial funding for publications appearing in original open-access journals ("Gold Open Access") as well as for articles in hybrid journals that are part of transformation contracts. The DESY library acquired the proportional funding within the framework of the DFG programme Open Access Publication Funding [1].

Figure 1

Participants in the FAIR transformation

This subsidy is the result of many years of efforts by the DESY library team to implement a detailed and well-organised infrastructure for capturing publication fees and processes, developed within the JOIN[2] collaboration and used by several partners. Since 2015 already, methods have been established in this context to support the scientists, fostering the open-access transformation of the publishing system. The significance of the now-digital approval workflow (see previous page) as an important part of this structure also becomes evident here.

openCost

As a coherent consequence, the DFG project openCost [2] sketches a next, necessary and sensible step towards reforming the publishing system. OpenCost highlights the necessity to make publication costs FAIR (findable, accessible, interoperable and reusable). Together with the libraries of the Universities of Bielefeld and Regensburg, Germany, and the partners from JOIN[2], a technical system is to be elaborated to extensively capture the total costs of publishing and make them openly accessible in a standardised manner.

This aim is to be achieved by implementing interfaces and developing a metadata schema that depicts not only the so-called article processing charges (APCs), but also costs that have so far often not been negotiated transparently or appear as non-justifiable adoptions of conventions exclusively for the print publication sector. Comparability of costs within and between different institutions in the field of scientific publishing needs to be ensured.

PUNCH4NFDI

Transparency and fairness should be natural concepts of scientific practice. As envisioned for publishing costs and processes, the DESY library and documentation group intends to extend its ambitions to scientific data and metadata. Within the scope of the DFG-funded project PUNCH4NFDI [3], the DESY library contributes expertise regarding the elaboration of FAIR metadata for the particle, astroparticle, nuclei and hadron physics communities in order to make highly heterogeneous data sustainable, relying on a common strategy. Science should not depend on a question of fair conditions.

Contact:
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References:

https://join2.de
[1] PubDB Publication Costs, https://bib-pubdb1.desy.de/record/474846
DFG Publication Costs,
https://gepris.dfg.de/gepris/projekt/491245950?language=en
[2] PubDB openCost, https://bib-pubdb1.desy.de/record/160800
DFG openCost, https://gepris.dfg.de/gepris/projekt/457354095?language=en
[3] PubDB PUNCH4NFDI, https://bib-pubdb1.desy.de/record/465698
DFG PUNCH4NFDI,
https://gepris.dfg.de/gepris/projekt/460248186?language=en


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Publications

ALPS

Published

P. Agrawal et al.
Feebly-interacting particles: FIPs 2020 workshop report.
The European physical journal / C, 81(11):1015, and PUBDB-2022-00284, arXiv:2102.12143.
doi: 10.1140/epjc/s10052-021-09703-7.

C. Albrecht et al.
Straightening of superconducting HERA dipoles for the any-light-particle-search experiment ALPS II.
EPJ Techniques and Instrumentation, 8:5(1):1, and PUBDB-2021-00731, arXiv:2004.13441. DESY-20-070.
doi: 10.1140/epjti/s40485-020-00060-5.

G. Ballesteros et al.
Revisiting isocurvature bounds in models unifying the axion with the inflaton.
Journal of cosmology and astroparticle physics, 2021(09):036 (1, and PUBDB-2021-04107, arXiv:2104.13847. IFT-UAM/CSIC-21-45. DESY-21-048. TUM-HEP-1334-21.
doi: 10.1088/1475-7516/2021/09/036.

L. Di Luzio et al.
An even lighter QCD axion.
Journal of high energy physics, 2021(5):184 (1, and PUBDB-2021-02793, DESY-21-010. IFT-UAM/CSIC-20-143. FTUAM-20-21. arXiv:2102.00012.
doi: 10.1007/JHEP05(2021)184.

L. Di Luzio et al.
Dark matter from an even lighter QCD axion: trapped misalignment.
Journal of cosmology and astroparticle physics, 2021(10):001, and PUBDB-2021-04106, DESY-21-011. IFT-UAM/CSIC-20-144. FTUAM-20-21. arXiv:2102.01082.
doi: 10.1088/1475-7516/2021/10/001.

O. Gerberding and K.-S. Isleif.
Ghost Beam Suppression in Deep Frequency Modulation Interferometry for Compact On-Axis Optical Heads.
Sensors, 21(5):1708, and PUBDB-2021-01803.
doi: 10.3390/s21051708.

IAXO Collaboration.
Conceptual design of BabyIAXO, the intermediate stage towards the International Axion Observatory.
Journal of high energy physics, 05(5):137, and PUBDB-2022-00309, arXiv:2010.12076.
doi: 10.1007/JHEP05(2021)137.

S. Knirck et al.
Simulating MADMAX in 3D: requirements for dielectric axion haloscopes.
Journal of cosmology and astroparticle physics, 2021(10):034 (1, and PUBDB-2021-04105, arXiv:2104.06553. MPP-2021-61. DESY-21-051.
doi: 10.1088/1475-7516/2021/10/034.

C. Reinhardt et al.
Gas cooling of test masses for future gravitational-wave observatories.
Classical and quantum gravity, 38(18):185003, and PUBDB-2022-00270, arXiv:2101.09164.
doi: 10.1088/1361-6382/ac18bc.

A. Ringwald, K. Saikawa and C. Tamarit.
Primordial gravitational waves in a minimal model of particle physics and cosmology.
Journal of cosmology and astroparticle physics, 2021(02):046, and PUBDB-2021-01098, arXiv:2009.02050. DESY-20-135. KANAZAWA-20-06. TUM-HEP-1279-20.
doi: 10.1088/1475-7516/2021/02/046.

A. Ringwald, J. Schütte-Engel and C. Tamarit.
Gravitational waves as a big bang thermometer.
Journal of cosmology and astroparticle physics, 2021(03):054, and PUBDB-2021-01467, DESY-20-187. TUM-HEP-1293-20. arXiv:2011.04731.
doi: 10.1088/1475-7516/2021/03/054.

R. Shah et al.
TES Detector for ALPS II.
1949394. The European Physical Society Conference on High Energy Physics (EPS-HEP2021), Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):801, and PUBDB-2021-04077, arXiv:2110.10654.
SISSA, Trieste.
doi: 10.22323/1.398.0801.

A. Sokolov and A. Ringwald.
Photophilic hadronic axion from heavy magnetic monopoles.
Journal of high energy physics, 2021(6):123 (1, and PUBDB-2021-02976, arXiv:2104.02574. DESY-21-046.
doi: 10.1007/JHEP06(2021)123.

ATLAS

Published

ATLAS Collaboration.
A search for the decays of stopped long-lived particles at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 2021(7):173, and PUBDB-2021-03395, arXiv:2104.03050. CERN-EP-2021-041.
doi: 10.1007/JHEP07(2021)173.

ATLAS Collaboration.
A search for the dimuon decay of the Standard Model Higgs boson with the ATLAS detector.
Physics letters / B, 812:135980 (1, and PUBDB-2020-05097, arXiv:2007.07830. CERN-EP-2020-117 CERN-EP-2020-117 CERN-EP-2020-117 CERN-EP-2020-117.
doi: 10.1016/j.physletb.2020.135980.

ATLAS Collaboration.
Configuration and performance of the ATLAS b-jet triggers in Run 2.
The European physical journal / C, 81(12):1087, and PUBDB-2021-05438, arXiv:2106.03584. CERN-EP-2021-032.
doi: 10.1140/epjc/s10052-021-09775-5.

ATLAS Collaboration.
Determination of the parton distribution functions of the proton from ATLAS measurements of differential $W^{\pm}$ and Z boson production in association with jets.
Journal of high energy physics, 07(7):223, and PUBDB-2021-04141, arXiv:2101.05095. CERN-EP-2020-237.
doi: 10.1007/JHEP07(2021)223.

ATLAS Collaboration.
Differential cross-section measurements for the electroweak production of dijets in association with a Z boson in proton–proton collisions at ATLAS.
The European physical journal / C, 81(2):163, and PUBDB-2021-05442, arXiv:2006.15458. CERN-EP-2020-045.
doi: 10.1140/epjc/s10052-020-08734-w.

ATLAS Collaboration.
Erratum 2 to: Search for the HH → $b\bar{b}b\bar{b}$ process via vector-boson fusion production using proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(5):207, and PUBDB-2022-00664, arXiv:2001.05178. CERN-EP-2019-267.
doi: 10.1007/JHEP05(2021)207.

ATLAS Collaboration.
Erratum to: Higgs boson production cross-section measurements and their EFT interpretation in the 4ℓ decay channel at $\sqrt{s}$ =13 TeV with the ATLAS detector.
The European physical journal / C, 81(5):398, and PUBDB-2022-00529, arXiv:2004.03447. CERN-EP-2020-034.
doi: 10.1140/epjc/s10052-021-09116-6.

ATLAS Collaboration.
Erratum to: Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector.
Journal of high energy physics, 2021(11):50, and PUBDB-2022-00645, arXiv:2008.05355. CERN-EP-2020-135.
doi: 10.1007/JHEP11(2021)050.

ATLAS Collaboration.
Erratum to: Search for phenomena beyond the Standard Model in events with large b-jet multiplicity using the ATLAS detector at the LHC.
The European physical journal / C, 81(3):249, and PUBDB-2022-00641, arXiv:2010.01015. CERN-EP-2020-147.
doi: 10.1140/epjc/s10052-021-08970-8.

ATLAS Collaboration.
Erratum to: Search for squarks and gluinos in final states with one isolated lepton, jets, and missing transverse momentum at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 81(10):956, and PUBDB-2022-00643, arXiv:2101.01629. CERN-EP-2020-228.
doi: 10.1140/epjc/s10052-021-09748-8.

ATLAS Collaboration.
Erratum to: Search for the HH → $b\bar{b}b\bar{b}$ process via vector-boson fusion production using proton-proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(1):145, and PUBDB-2022-00667, arXiv:2001.05178. CERN-EP-2019-267.
doi: 10.1007/JHEP01(2021)145.

ATLAS Collaboration.
Erratum: Search for new non-resonant phenomena in high-mass dilepton final states with the ATLAS detector.
Journal of high energy physics, 2021(4):142, and PUBDB-2022-00662, arXiv:2006.12946. CERN-EP-2020-066.
doi: 10.1007/JHEP04(2021)142.

ATLAS Collaboration.
Evidence for Higgs boson decays to a low-mass dilepton system and a photon in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Physics letters / B, 819:136412 (1, and PUBDB-2021-03422, arXiv:2103.10322. CERN-EP-2021-035.
doi: 10.1016/j.physletb.2021.136412.

ATLAS Collaboration.
Exclusive dimuon production in ultraperipheral Pb+Pb collisions at $\sqrt{s_{\rm NN}} = 5.02$ TeV with ATLAS.
Physical review / C, 104(2):024906, and PUBDB-2021-04154, arXiv:2011.12211. CERN-EP-2020-138.
doi: 10.1103/PhysRevC.104.024906.

ATLAS Collaboration.
Jet energy scale and resolution measured in proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 81(8):689, and PUBDB-2021-05443, arXiv:2007.02645. CERN-EP-2020-083.
doi: 10.1140/epjc/s10052-021-09402-3.

ATLAS Collaboration.
Longitudinal Flow Decorrelations in Xe + Xe Collisions at $\sqrt{s_{NN}}$ = 5.44 TeV with the ATLAS Detector.
Physical review letters, 126(12):122301 (1, and PUBDB-2021-05452, arXiv:2001.04201. CERN-EP-2019-275.
doi: 10.1103/PhysRevLett.126.122301.

M. W. O’Keefe.
Luminosity Determination using $Z \to \ell\ell$ events at $\sqrt{s}$ = 13TeV with the ATLAS detector.
1860188. 40th International Conference on High Energy Physics, Prague (Czechia), 30 Jul 2020 - 5 Aug 2020.
Proceedings of Science / International School for Advanced Studies, vol. (ICHEP2020):812, and PUBDB-2021-05364, ATL-DAPR-PUB-2021-001.
SISSA, Trieste.
doi: 10.22323/1.390.0812.

ATLAS Collaboration.
Measurement of b-quark fragmentation properties in jets using the decay $B^{\pm} \to J/\psi K^{\pm}$ in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(12):131, and PUBDB-2022-00181, arXiv:2108.11650. CERN-EP-2021-123.
doi: 10.1007/JHEP12(2021)131.

ATLAS Collaboration.
Measurement of hadronic event shapes in high-p_T multijet final states at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 01(1):188, and PUBDB-2021-02449, arXiv:2007.12600. CERN-EP-2020-077. arXiv:2007.12600. CERN-EP-2020-077.
doi: 10.1007/JHEP01(2021)188.

ATLAS Collaboration.
Measurement of light-by-light scattering and search for axion-like particles with 2.2 nb^{-1} of Pb+Pb data with the ATLAS detector.
Journal of high energy physics, 03(3):243, and PUBDB-2021-02437, arXiv:2008.05355. CERN-EP-2020-135.
doi: 10.1007/JHEP03(2021)243.

ATLAS Collaboration.
Measurement of single top-quark production in association with a W boson in the single-lepton channel at $\sqrt{s} = 8$ TeV with the ATLAS detector.
The European physical journal / C, 81(8):720 (1, and PUBDB-2021-05453, arXiv:2007.01554. CERN-EP-2019-221.
doi: 10.1140/epjc/s10052-021-09371-7.

ATLAS Collaboration.
Measurement of the CP-violating phase ϕ_s in $B_s^0 \to J/\psi\phi$ decays in ATLAS at 13 TeV.
The European physical journal / C, 81(4):342, and PUBDB-2022-00233, arXiv:2001.07115. CERN-EP-2019-218.
doi: 10.1140/epjc/s10052-021-09011-0.

ATLAS Collaboration.
Measurement of the associated production of a Higgs boson decaying into b-quarks with a vector boson at high transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Physics letters / B, 816:136204, and PUBDB-2021-02435, arXiv:2008.02508. CERN-EP-2020-093. arXiv:2008.02508. CERN-EP-2020-093.
doi: 10.1016/j.physletb.2021.136204.

ATLAS Collaboration.
Measurement of the jet mass in high transverse momentum $Z(\to b\bar{b})\gamma$ production at $\sqrt{s} = 13$ TeV using the ATLAS detector.
Physics letters / B, 812:135991, and PUBDB-2020-05256, arXiv:1907.07093. CERN-EP-2019-115.
doi: 10.1016/j.physletb.2020.135991.

ATLAS Collaboration.
Measurement of the production cross section of pairs of isolated photons in pp collisions at 13 TeV with the ATLAS detector.
Journal of high energy physics, 11:169, and PUBDB-2021-05176, arXiv:2107.09330. CERN-EP-2021-105.
doi: 10.1007/JHEP11(2021)169.

ATLAS Collaboration.
Measurement of the relative $B_c^\pm/B^\pm$ production cross section with the ATLAS detector at $\sqrt{s} = 8$ TeV.
Physical review / D, 104(1):012010, and PUBDB-2022-00622, arXiv:1912.02672. CERN-EP-2019-194.
doi: 10.1103/PhysRevD.104.012010.

ATLAS Collaboration.
Measurement of the $t\bar{t}t\bar{t}$ production cross section in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 11(11):118, and PUBDB-2021-05334, arXiv:2106.11683. CERN-EP-2021-075.
doi: 10.1007/JHEP11(2021)118.

ATLAS Collaboration.
Measurements of differential cross-sections in four-lepton events in 13 TeV proton-proton collisions with the ATLAS detector.
Journal of high energy physics, 2021(7):5, and PUBDB-2021-03423, arXiv:2103.01918. CERN-EP-2021-019.
doi: 10.1007/JHEP07(2021)005.

ATLAS Collaboration.
Measurements of Higgs Bosons Decaying to Bottom Quarks from Vector Boson Fusion Production with the ATLAS Experiment at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(6):537, and PUBDB-2021-04165, arXiv:2011.08280. CERN-EP-2020-195.
doi: 10.1140/epjc/s10052-021-09192-8.

ATLAS Collaboration.
Measurements of sensor radiation damage in the ATLAS inner detector using leakage currents.
Journal of Instrumentation, 16(08):P08025, and PUBDB-2021-03394, arXiv:2106.09287. CERN-EP-2021-055.
doi: 10.1088/1748-0221/16/08/P08025.

ATLAS Collaboration.
Measurements of the inclusive and differential production cross sections of a top-quark-antiquark pair in association with a Z boson at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 81(8):737, and PUBDB-2021-05473, arXiv:2103.12603. CERN-EP-2021-01.
doi: 10.1140/epjc/s10052-021-09439-4.

ATLAS Collaboration.
Measurements of top-quark pair single- and double-differential cross-sections in the all-hadronic channel in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector.
Journal of high energy physics, 2021(1):33, and PUBDB-2021-05474, arXiv:2006.09274. CERN-EP-2020-063.
doi: 10.1007/JHEP01(2021)033.

ATLAS Collaboration.
Measurements of $W^+W^- + \geq 1$ jet production cross-sections in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(6):3 (1, and PUBDB-2021-03421, arXiv:2103.10319. CERN-EP-2021-030.
doi: 10.1007/JHEP06(2021)003.

ATLAS Collaboration.
Measurements of WH and ZH production in the $H \to b\bar{b}$ decay channel in pp collisions at 13 TeV with the ATLAS detector.
The European physical journal / C, 81(2):178 (1, and PUBDB-2021-05454, arXiv:2007.02873. CERN-EP-2020-087.
doi: 10.1140/epjc/s10052-020-08677-2.

ATLAS Collaboration.
Medium-induced modification of Z-tagged charged particle yields in Pb+Pb collisions at 5.02 TeV with the ATLAS detector.
Physical review letters, 126(7):072301, and PUBDB-2021-02418, arXiv:2008.09811. CERN-EP-2020-148.
doi: 10.1103/PhysRevLett.126.072301.

ATLAS Collaboration.
Muon reconstruction and identification efficiency in ATLAS using the full Run 2 pp collision data set at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(7):578, and PUBDB-2021-04152, arXiv:2012.00578. CERN Preprint ID: CERN-EP-2020-199. arXiv:2012.00578. CERN-EP-2020-199.
doi: 10.1140/epjc/s10052-021-09233-2.

ATLAS Collaboration.
Observation of photon-induced W^+W^- production in pp collisions at $\sqrt{s} = 13$ TeV using the ATLAS detector.
Physics letters / B, 816:136190 (1, and PUBDB-2021-02238, arXiv:2010.04019. CERN-EP-2020-165.
doi: 10.1016/j.physletb.2021.136190.

ATLAS Collaboration.
Operation and performance of the ATLAS semiconductor tracker in LHC Run 2.
Journal of Instrumentation, 17(01):P01013, and PUBDB-2022-00876, arXiv:2109.02591. CERN-EP-2021-178.
doi: 10.1088/1748-0221/17/01/P01013.

ATLAS Collaboration.
Optimisation of large-radius jet reconstruction for the ATLAS detector in 13 TeV proton–proton collisions.
The European physical journal / C, 81(4):334, and PUBDB-2021-02419, arXiv:2009.04986. CERN-EP-2020-134.
doi: 10.1140/epjc/s10052-021-09054-3.

ATLAS Collaboration.
Performance of the ATLAS RPC detector and Level-1 muon barrel trigger at √(s)=13 TeV.
Journal of Instrumentation, 16(07):P07029 (1, and PUBDB-2021-03424, arXiv:2103.01029. CERN-EP-2020-245.
doi: 10.1088/1748-0221/16/07/P07029.

ATLAS Collaboration.
Search for a heavy Higgs boson decaying into a Z boson and another heavy Higgs boson in the $\ell\ell bb$ and $\ell\ell WW$ final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
The European physical journal / C, 81(5):396, and PUBDB-2021-02240, arXiv:2011.05639. CERN-EP-2020-191.
doi: 10.1140/epjc/s10052-021-09117-5.

ATLAS Collaboration.
Search for bottom-squark pair production in pp collision events at $\sqrt{s} = 13$ TeV with hadronically decaying τ-leptons, b-jets and missing transverse momentum using the ATLAS detector.
Physical review / D, 104(3):032014, and PUBDB-2021-04129, arXiv:2103.08189. CERN-EP-2020-235.
doi: 10.1103/PhysRevD.104.032014.

ATLAS Collaboration.
Search for charged Higgs bosons decaying into a top quark and a bottom quark at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(6):145, and PUBDB-2021-03400, arXiv:2102.10076. CERN-EP-2021-004.
doi: 10.1007/JHEP06(2021)145.

ATLAS Collaboration.
Search for dark matter in association with an energetic photon in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(2):226 (1, and PUBDB-2021-01629, arXiv:2011.05259. CERN-EP-2020-178.
doi: 10.1007/JHEP02(2021)226.

ATLAS Collaboration.
Search for dark matter in events with missing transverse momentum and a Higgs boson decaying into two photons in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 10:013, and PUBDB-2021-04125, arXiv:2104.13240. CERN-EP-2021-012.
doi: 10.1007/JHEP10(2021)013.

ATLAS Collaboration.
Search for Dark Matter Produced in Association with a Dark Higgs Boson Decaying into $W^\pm W^\mp$ or ZZ in Fully Hadronic Final States from $\sqrt{s} = 13$ TeV pp Collisions Recorded with the ATLAS Detector.
Physical review letters, 126(12):121802, and PUBDB-2021-02239, arXiv:2010.06548. CERN-EP-2020-172. arXiv:2010.06548. CERN-EP-2020-172.
doi: 10.1103/PhysRevLett.126.121802.

J. von Ahnen.
Search for Dark Matter produced in association with a Higgs boson decaying to b-quarks using the ATLAS detector.
1971345. 9th Edition of the Large Hadron Collider Physics Conference, online (virtuell world), 7 Jun 2021 - 12 Jun 2021.
Proceedings of Science / International School for Advanced Studies, vol. (LHCP2021):255, and PUBDB-2021-05208.
SISSA, Trieste.
doi: 10.22323/1.397.0255.

ATLAS Collaboration.
Search for dark matter produced in association with a single top quark in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
The European physical journal / C, 81:860, and PUBDB-2021-04157, arXiv:2011.09308. CERN-EP-2020-184.
doi: 10.1140/epjc/s10052-021-09566-y.

ATLAS Collaboration.
Search for dark matter produced in association with a Standard Model Higgs boson decaying into b-quarks using the full Run 2 dataset from the ATLAS detector.
Journal of high energy physics, 11:209, and PUBDB-2021-05332, arXiv:2108.13391. CERN-EP-2021-074.
doi: 10.1007/JHEP11(2021)209.

ATLAS Collaboration.
Search for displaced leptons in $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
Physical review letters, 127(5):051802, and PUBDB-2021-04166, arXiv:2011.07812. CERN-EP-2020-205.
doi: 10.1103/PhysRevLett.127.051802.

ATLAS Collaboration.
Search for doubly and singly charged Higgs bosons decaying into vector bosons in multi-lepton final states with the ATLAS detector using proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 2021(6):146 (1, and PUBDB-2021-03429, arXiv:2101.11961. CERN-EP-2020-240.
doi: 10.1007/JHEP06(2021)146.

ATLAS Collaboration.
Search for exotic decays of the Higgs boson into long-lived particles in pp collisions at $\sqrt{s}$ = 13 TeV using displaced vertices in the ATLAS inner detector.
Journal of high energy physics, 11(11):229, and PUBDB-2022-00510, arXiv:2107.06092.
doi: 10.1007/JHEP11(2021)229.

ATLAS Collaboration.
Search for heavy resonances decaying into a pair of Z bosons in the $\ell^+\ell^-\ell'^+\ell'^-$ and $\ell^+\ell^-\nu\bar{\nu}$ final states using 139 fb^{-1} of proton–proton collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
The European physical journal / C, 81(4):332, and PUBDB-2021-02364, arXiv:2009.14791. CERN-EP-2020-153.
doi: 10.1140/epjc/s10052-021-09013-y.

ATLAS Collaboration.
Search for Higgs boson decays into a pair of pseudoscalar particles in the $bb\mu\mu$ final state with the ATLAS detector in pp collisions at $\sqrt{s}$=13 TeV.
Physical review / D, 105(1):012006, and PUBDB-2022-00875, arXiv:2110.00313. CERN-EP-2021-157.
doi: 10.1103/PhysRevD.105.012006.

ATLAS Collaboration.
Search for Higgs boson production in association with a high-energy photon via vector-boson fusion with decay into bottom quark pairs at $\sqrt{s}$=13 TeV with the ATLAS detector.
Journal of high energy physics, 03(3):268 (1, and PUBDB-2021-01980, arXiv:2010.13651. CERN-EP-2020-179.
doi: 10.1007/JHEP03(2021)268.

ATLAS Collaboration.
Search for new phenomena in events with an energetic jet and missing transverse momentum in pp collisions at $\sqrt{s}$ =13 TeV with the ATLAS detector.
Physical review / D, 103(11):112006, and PUBDB-2021-03426, arXiv:2102.10874. CERN-EP-2020-238.
doi: 10.1103/PhysRevD.103.112006.

ATLAS Collaboration.
Search for new phenomena in events with two opposite-charge leptons, jets and missing transverse momentum in pp collisions at $\sqrt{s} = 13$ TeV with the ATLAS detector.
Journal of high energy physics, 04(4):165 (1, and PUBDB-2021-01908, arXiv:2102.01444. CERN-EP-2020-243.
doi: 10.1007/JHEP04(2021)165.

ATLAS Collaboration.
Search for new phenomena with top quark pairs in final states with one lepton, jets, and missing transverse momentum in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 04(4):174, and PUBDB-2021-02448, arXiv:2012.03799. CERN-EP-2020-177.
doi: 10.1007/JHEP04(2021)174.

ATLAS Collaboration.
Search for pair production of scalar leptoquarks decaying into first- or second-generation leptons and top quarks in proton–proton collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
The European physical journal / C, 81(4):313, and PUBDB-2021-02362, arXiv:2010.02098. CERN-EP-2020-160. arXiv:2010.02098. CERN-EP-2020-160.
doi: 10.1140/epjc/s10052-021-09009-8.

ATLAS Collaboration.
Search for pair production of third-generation scalar leptoquarks decaying into a top quark and a τ-lepton in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Journal of high energy physics, 2021(6):179, and PUBDB-2021-03430, arXiv:2101.11582. CERN-EP-2020-241.
doi: 10.1007/JHEP06(2021)179.

ATLAS Collaboration.
Search for phenomena beyond the Standard Model in events with large b-jet multiplicity using the ATLAS detector at the LHC.
The European physical journal / C, 81(3):11, and PUBDB-2021-02363, arXiv:2010.01015. CERN-EP-2020-147. arXiv:2010.01015. CERN-EP-2020-147.
doi: 10.1140/epjc/s10052-020-08730-0.

ATLAS Collaboration.
Search for R-parity-violating supersymmetry in a final state containing leptons and many jets with the ATLAS experiment using $\sqrt{s} = 13TeV$ proton–proton collision data.
The European physical journal / C, 81(11):1023, and PUBDB-2021-05439, arXiv:2106.09609. CERN-EP-2021-066.
doi: 10.1140/epjc/s10052-021-09761-x.

ATLAS Collaboration.
Search for resonances decaying into photon pairs in 139 fb^{-1} of pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
Physics letters / B, 822:136651, and PUBDB-2021-04126, arXiv:2102.13405. CERN-EP-2020-248.
doi: 10.1016/j.physletb.2021.136651.

ATLAS Collaboration.
Search for squarks and gluinos in final states with jets and missing transverse momentum using 139 fb^{-1} of $\sqrt{s}$ =13 TeV pp collision data with the ATLAS detector.
Journal of high energy physics, 02(2):143 (1, and PUBDB-2021-01979, arXiv:2010.14293. CERN-EP-2020-166.
doi: 10.1007/JHEP02(2021)143.

ATLAS Collaboration.
Search for squarks and gluinos in final states with one isolated lepton, jets, and missing transverse momentum at $\sqrt{s} = 13$ with the ATLAS detector.
The European physical journal / C, 81(7):600, and PUBDB-2021-04139, arXiv:2101.01629. CERN-EP-2020-228.
doi: 10.1140/epjc/s10052-021-09344-w.

ATLAS Collaboration.
Search for supersymmetry in events with four or more charged leptons in $139\,\mathbf{fb}^{-1}$ of $\sqrt{s} = 13$ TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 2021(7):167, and PUBDB-2021-04499, arXiv:2103.11684. CERN-EP-2021-021.
doi: 10.1007/JHEP07(2021)167.

ATLAS Collaboration.
Search for trilepton resonances from chargino and neutralino pair production in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Physical review / D, 103:112003, and PUBDB-2021-04156, arXiv:2011.10543. CERN-EP-2020-201.
doi: 10.1103/PhysRevD.103.112003.

ATLAS Collaboration.
Search for type-III seesaw heavy leptons in dilepton final states in pp collisions at $\sqrt{s}$ = 13 TeV with the ATLAS detector.
The European physical journal / C, 81(3):218, and PUBDB-2021-02438, arXiv:2008.07949. CERN-EP-2020-130.
doi: 10.1140/epjc/s10052-021-08929-9.

ATLAS Collaboration.
The ATLAS Fast TracKer system.
Journal of Instrumentation, 16(07):P07006, and PUBDB-2021-04140, arXiv:2101.05078. CERN-EP-2020-232.
doi: 10.1088/1748-0221/16/07/P07006.

ATLAS Collaboration.
Two-particle azimuthal correlations in photonuclear ultraperipheral Pb+Pb collisions at 5.02 TeV with ATLAS.
Physical review / C, 104(1):014903, and PUBDB-2021-03431, arXiv:2101.10771. CERN-EP-2020-246.
doi: 10.1103/PhysRevC.104.014903.

Atlas Collaboration.
Search for new phenomena in final states with b-jets and missing transverse momentum in $\sqrt{s}$ = 13 TeV pp collisions with the ATLAS detector.
Journal of high energy physics, 2021(5):93 (1, and PUBDB-2021-03428, arXiv:2101.12527. CERN-EP-2021-001.
doi: 10.1007/JHEP05(2021)093.

T. Novak.
ATLAS + CMS searches beyond inclusive resonances in leptonic final states.
1971333. 9th Large Hadron Collider Physics Conference, Paris (France), 7 Jun 2021 - 12 Jun 2021.
Proceedings of Science / International School for Advanced Studies, vol. (LHCP2021):281, and PUBDB-2021-05622.
SISSA, Trieste.
doi: 10.22323/1.397.0281.

F. Berghaus et al.
ATLAS in-file metadata and multi-threaded processing.
25th International Conference on Computing in High-Energy and Nuclear Physics, Online (France), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03006, and PUBDB-2021-05621.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103006.

M. Blanke et al.
Single-top final states as a probe of top-flavoured dark matter models at the LHC.
Journal of high energy physics, 2021(1):194, and PUBDB-2021-03171, TTP20-034. P3H-20-059. DESY-21-041. arXiv:2010.10530.
doi: 10.1007/JHEP01(2021)194.

D. Cameron et al.
Evolution of ATLAS analysis workflows and tools for the HL-LHC era.
The European physical journal / Web of Conferences, 251:02002, and PUBDB-2022-00114.
doi: 10.1051/epjconf/202125102002.

R. Capdevilla et al.
Hunting wino and higgsino dark matter at the muon collider with disappearing tracks.
Journal of high energy physics, 06(6):133, and PUBDB-2021-05615, arXiv:2102.11292. DESY-21-019. IFIC/21-03.
doi: 10.1007/JHEP06(2021)133.

S. Carra et al.
Constraining off-shell production of axionlike particles with Zγ and WW differential cross-section measurements.
Physical review / D, 104(9):092005, and PUBDB-2021-04872, arXiv:2106.10085. DESY-21-063.
doi: 10.1103/PhysRevD.104.092005.

D. Dannheim et al.
Corryvreckan: a modular 4D track reconstruction and analysis software for test beam data.
Journal of Instrumentation, 16(03):P03008, and PUBDB-2021-04949, arXiv:2011.12730. CLICdp-Pub-2020-005. DESY-20-210.
doi: 10.1088/1748-0221/16/03/P03008.

A. Forti et al.
The fight against COVID-19: Running Folding@Home simulations on ATLAS resources.
The European physical journal / Web of Conferences, 251:02003, and PUBDB-2022-00115.
doi: 10.1051/epjconf/202125102003.

B. Fuks et al.
Majorana neutrinos in same-sign $W^\pm$ $W^\pm$ scattering at the LHC: Breaking the TeV barrier.
Physical review / D, 103(5):055005, and PUBDB-2021-02535, arXiv:2011.02547. CP3-20-50. DESY-20-186. MCNet-20-24. IFJPAN-IV-2021-2. VBSCAN-PUB-11-20.
doi: 10.1103/PhysRevD.103.055005.

B. Fuks et al.
Probing the Weinberg operator at colliders.
Physical review / D, 103(11):115014, and PUBDB-2021-03081, arXiv:2012.09882. CP3-20-63. DESY-20-230. IFJPAN-IV-2021-3. MCNet-20-23.
doi: 10.1103/PhysRevD.103.115014.

N. E. K. Gillwald.
Background Modelling in the ATLAS $H \to \gamma\gamma$ Differential Cross Section Analysis.
European Physical Society Conference on High Energy Physics, online (virtual world), 26 Jul 2021 - 30 Jul 2021.

Proceedings of Science / International School for Advanced Studies, vol. 398:572, and PUBDB-2021-05580.
SISSA, Trieste.
doi: 10.22323/1.398.0572.

LHeC Collaboration.
The Large Hadron-Electron Collider at the HL-LHC.
Journal of physics / G, 48(11):110501, and PUBDB-2022-00307, arXiv:2007.14491. CERN-ACC-Note-2020-0002. JLAB-ACP-20-3180.
doi: 10.1088/1361-6471/abf3ba.

P. Moder.
Measuring luminosity with track counting in the ATLASexperiment.
1860187. 40th International Conference on High Energy Physics, Prague (online) (Czech Republic), 28 Jul 2021 - 6 Aug 2021.
Proceedings of Science / International School for Advanced Studies, vol. (ICHEP2020):811, and PUBDB-2021-05274, ATL-DAPR-PROC-2020-002.
SISSA, Trieste.
doi: 10.22323/1.390.0811.

A.-L. Poley et al.
Mapping the material distribution of a complex structure in an electron beam.
Journal of Instrumentation, 16(01):P01010, and PUBDB-2021-00508, arXiv:2105.10128.
doi: 10.1088/1748-0221/16/01/P01010.

Ph.D. Thesis

A. Basalaev.
Evidence for Higgs boson decays to a low mass lepton pair and a photon with the ATLAS detector at the LHC.
University of Hamburg, 2021.

Y. Delabat Diaz.
Search for Standard Model Higgs bosons produced in association with top-quark pairs in ttH multilepton final states using the ATLAS detector at the LHC.
Humboldt-Universitat zu Berlin: 2021.

F. Nechansky.
Search for the production of a Higgs boson decaying into a pair of bottom quarks in association with a pair of top quarks at 13 TeV with the ATLAS detector.
Humboldt Universität zu Berlin, 2021.

G. Pownall.
QCD analysis and measurement of W boson production in association with jets at the ATLAS detector.
University of Oxford, 2021.

J. Sabater Iglesias.
Welcome to Twin Particles: From Novel ZZ Estimate to Searches for Supersymmetric Sleptons and Higgsinos using the ATLAS Run-2 Data and at the High-Luminosity LHC.
Albert Ludwig University of Freiburg, 2021.

M. Stanescu-Bellu.
Search for heavy Higgs bosons A/H decaying to a top-quark pair in pp collisions at $\sqrt{(s)} = 8$ TeV with the ATLAS detector.
Humboldt Universität zu Berlin, 2021.

M. Stegler.
Studies on the Influence of Mechanical Stresson the Properties of Silicon Sensor Modules for the ATLAS Phase-II Upgrade.
Brandenburgischen Technischen Universität Cottbus-Senftenberg, 2021.

Belle

Published

A. Abdesselam et al.
Test of lepton flavor universality and search for lepton flavor violation in B → Kℓℓ decays.
Journal of high energy physics, 2021(3):105 (1, and PUBDB-2021-01708, arXiv:1908.01848. BELLE-CONF-1904.
doi: 10.1007/JHEP03(2021)105.

Belle Collaboration.
Erratum: Measurement of the CKM matrix element $|V_{cb}|$ from $B^0 \to D^{*-}\ell^+\nu_\ell$ at Belle [Phys. Rev. D 100 , 052007 (2019)].
Physical review / D, 103(7):079901, and PUBDB-2022-00227, arXiv:1809.03290.
doi: 10.1103/PhysRevD.103.079901.

Belle Collaboration.
Evidence for $X(3872) \to J/\psi\pi^+\pi^-$ Produced in Single-Tag Two-Photon Interactions.
Physical review letters, 126(12):122001 (1, and PUBDB-2021-01705, arXiv:2007.05696. Belle Preprint 2020-08. KEK Preprint 2020-07.
doi: 10.1103/PhysRevLett.126.122001.

Belle Collaboration.
Evidence for the decay $\Omega_c^0 \to \pi^+\Omega(2012)^- \to \pi^+(K^-\Xi)^-$.
Physical review / D, 104(5):052005, and PUBDB-2021-04612, arXiv:2106.00892. Belle Preprint 2021-10. KEK Preprint 2021-6.
doi: 10.1103/PhysRevD.104.052005.

Belle Collaboration.
First determination of the spin and parity of the charmed-strange baryon $\Xi_c(2970)^+$.
Physical review / D, 103(11):L111101, and PUBDB-2021-04415.
doi: 10.1103/PhysRevD.103.L111101.

Belle Collaboration.
Measurement of branching fraction and search for CP violation in $B \to \phi\phi K$.
Physical review / D, 103(5):052013 (1, and PUBDB-2021-01690, arXiv:2101.07753. Belle Preprint 2020-20. KEK Preprint 2020-37.
doi: 10.1103/PhysRevD.103.052013.

Belle Collaboration.
Measurement of branching fractions and CP asymmetries for $D_s^+ \to K^+(\eta, \pi^0)$ and $D_s^+ \to \pi^+(\eta, \pi^0)$ decays at Belle.
Physical review / D, 103(11):112005, and PUBDB-2021-04566, arXiv:2103.09969. Belle Preprint 2021-04. KEK Preprint 2020-46. UC Preprint UCHEP-21-02.
doi: 10.1103/PhysRevD.103.112005.

Belle Collaboration.
Measurement of branching fractions and search for CP violation in $D^0 \to \pi^+\pi^-\eta$, $D^0 \to K^+K^-\eta$, and $D^0 \to \phi\eta$ at Belle.
Journal of high energy physics, 09(9):075, and PUBDB-2021-04712, arXiv:2106.04286. KEK Preprint 2021-8. Belle Preprint 2021-11. UCHEP-21-03.
doi: 10.1007/JHEP09(2021)075.

Belle Collaboration.
Measurement of branching fractions of $\Lambda_c^+ \to \eta\Lambda\pi^+, \eta\Sigma^0\pi^+, \Lambda(1670)\pi^+$, and $\eta\Sigma(1385)^+$.
Physical review / D, 103(5):052005 (1, and PUBDB-2021-01706, arXiv:2008.11575.
doi: 10.1103/PhysRevD.103.052005.

Belle Collaboration.
Measurement of Differential Branching Fractions of Inclusive $B \to X_u \ell^+ \nu_\ell$ Decays.
Physical review letters, 127(26):261801, and PUBDB-2021-05691, arXiv:2107.13855. Belle Preprint 2021-15. KEK Preprint 2021-13.
doi: 10.1103/PhysRevLett.127.261801.

Belle Collaboration.
Measurement of the branching fraction of $\Lambda_c^+ \to p\omega$ decay at Belle.
Physical review / D, 104(7):072008, and PUBDB-2021-04732, arXiv:2108.11301. Belle Preprint 2021-19. KEK Preprint 2021-23.
doi: 10.1103/PhysRevD.104.072008.

Belle Collaboration.
Measurement of the branching fraction of the decay $B^+ \to \pi^+\pi^-\ell^+\nu_\ell$ in fully reconstructed events at Belle.
Physical review / D, 103(11):112001, and PUBDB-2021-04736, arXiv:2005.07766. Belle preprint 2020-06. KEK preprint 2020-04.
doi: 10.1103/PhysRevD.103.112001.

Belle Collaboration.
Measurement of the energy dependence of the $e^+e^- \to B\overline{B}, B\overline{B}^*$ and $B^*\overline{B}^*$ exclusive cross sections.
Journal of high energy physics, 06(6):137, and PUBDB-2021-04609, arXiv:2104.08371. Belle Preprint 2021-05. KEK Preprint 2021-1.
doi: 10.1007/JHEP06(2021)137.

Belle Collaboration.
Measurement of the masses and widths of the $\Sigma_c(2455)^+$ and $\Sigma_c(2520)^+$ baryons.
Physical review / D, 104(5):052003, and PUBDB-2021-04730, arXiv:2107.05615. Belle Preprint 2021-14. KEK Preprint 2021-11.
doi: 10.1103/PhysRevD.104.052003.

Belle Collaboration.
Measurement of the Resonant and Non-Resonant Branching Ratios in $\Xi_c^0 \to \Xi^0 K^+ K^-$.
Physical review / D, 103(11):112002, and PUBDB-2021-04540, arXiv:2012.05607.
doi: 10.1103/PhysRevD.103.112002.

Belle Collaboration.
Measurement of time-dependent CP violation parameters in $B^0 \to K^{SKSKS}_{0\;0\;0}$ decays at Belle.
Physical review / D, 103(3):032003 (1, and PUBDB-2021-00896.
doi: 10.1103/PhysRevD.103.032003.

Belle Collaboration.
Measurements of branching fractions and asymmetry parameters of $\Xi_c^0 \to \Lambda\bar{K}^{*0}$, $\Xi_c^0 \to \Sigma^0\bar{K}^{*0}$, and $\Xi_c^0 \to \Sigma^+K^{*-}$ decays at Belle.
Journal of high energy physics, 06(6):160, and PUBDB-2021-04604, arXiv:2104.10361. Belle Preprint 2021-06. KEK Preprint 2021-2.
doi: 10.1007/JHEP06(2021)160.

Belle Collaboration.
Measurements of Partial Branching Fractions of Inclusive $B \to X_u \ell^+ \nu_\ell$ Decays with Hadronic Tagging.
Physical review / D, 104(1):012008, and PUBDB-2021-04545, arXiv:2102.00020. Belle Preprint 2020-22. KEK Preprint 2020-39.
doi: 10.1103/PhysRevD.104.012008.

Belle Collaboration.
Measurements of the branching fractions of $\Lambda_c^+ \to p\eta$ and $\Lambda_c^+ \to p\pi^0$ decays at Belle.
Physical review / D, 103(7):072004, and PUBDB-2021-02600, arXiv:2102.12226. Belle Preprint 2021-02. KEK Preprint 2020-42.
doi: 10.1103/PhysRevD.103.072004.

Belle Collaboration.
Measurements of the branching fractions of semileptonic decays $\Xi_c^0 \to \Xi^-\ell^+\nu_\ell$ and asymmetry parameter of $\Xi_c^0 \to \Xi^-\pi^+$ decay.
Physical review letters, 127(12):121803, and PUBDB-2021-04565, arXiv:2103.06496. Belle Preprint 2021-03. KEK Preprint 2020-44.
doi: 10.1103/PhysRevLett.127.121803.

Belle Collaboration.
Search for $B_s^0 \to \eta' X_{s\bar{s}}$ at Belle Using a Semi-Inclusive Method.
Physical review / D, 104(1):012007, and PUBDB-2021-04546, arXiv:2102.10266. Belle Preprint 2021-01. KEK Preprint 2020-40.
doi: 10.1103/PhysRevD.104.012007.

Belle Collaboration.
Search for $B^0 \to \tau^\pm\ell^\mp$ ($\ell = e, \mu$) with a hadronic tagging method at Belle.
Physical review / D, 104(9):L091105, and PUBDB-2021-05241, Belle Preprint 2021-23. KEK Preprint 2021-27. UC Preprint UCHEP-21-04. arXiv:2108.11649.
doi: 10.1103/PhysRevD.104.L091105.

Belle Collaboration.
Search for lepton-flavor-violating tau-lepton decays to $\ell\gamma$ at Belle.
Journal of high energy physics, 2021(10):019, and PUBDB-2021-04610, arXiv:2103.12994. arXiv:2103.12994.
doi: 10.1007/JHEP10(2021)019.

Belle Collaboration.
Search for the $\eta_{c2}(1D)$ in $e^+e^- \to \gamma\eta_{c2}(1D)$ at $\sqrt{s}$ near 10.6 GeV at Belle.
Physical review / D, 104(1):012012, and PUBDB-2021-04715, arXiv:2106.09224. Belle Preprint 2021-12. KEK Preprint 2021-9.
doi: 10.1103/PhysRevD.104.012012.

Belle Collaboration.
Search for the dark photon in $B^0 \to A'A', A' \to e^+e^-, \mu^+\mu^-$, and $\pi^+\pi^-$ decays at Belle.
Journal of high energy physics, 2021(4):191, and PUBDB-2021-02604, arXiv:2012.02538. Belle Preprint 2020-19. KEK Preprint 2020-36.
doi: 10.1007/JHEP04(2021)191.

Belle Collaboration.
Search for the decay $B_s^0 \to \eta'\eta$.
Physical review / D, 104(3):L031101, and PUBDB-2021-04718, arXiv:2106.09695. Belle Preprint No. 2021-13. KEK Preprint No. 2021-10.
doi: 10.1103/PhysRevD.104.L031101.

Belle Collaboration.
Study of $e^+e^- \to \Upsilon(1S, 2S)$ and $e^+e^- \to \Upsilon(1S)'$ at $\sqrt{s} = 10.866$ GeV with the Belle detector.
Physical review / D, 104(11):112006, and PUBDB-2021-05642, arXiv:2108.04426. Belle Preprint 2021-16. KEK Preprint 2021-14.
doi: 10.1103/PhysRevD.104.112006.

Belle Collaboration.
Test of lepton flavor universality in $B \to K^*\ell^+\ell^-$ decays at Belle.
Physical review letters, 126(16):161801, and PUBDB-2021-04537, BELLE-CONF-1901. arXiv:1904.02440.
doi: 10.1103/PhysRevLett.126.161801.

Belle-II Collaboration.
Precise measurement of the D^0 and D^+ lifetimes at Belle II.
Physical review letters, 127(21):211801 (1, and PUBDB-2022-00060, arXiv:2108.03216. Belle II Preprint 2021-002. KEK Preprint 2021-12.
doi: 10.1103/PhysRevLett.127.211801.

Belle-II Collaboration.
Search for $B^+ \to K^+\nu\bar{\nu}$ Decays Using an Inclusive Tagging Method at Belle II.
Physical review letters, 127(18):181802 (1, and PUBDB-2022-00057, arXiv:2104.12624. Belle II Preprint 2021-001. KEK Preprint 2020-45.
doi: 10.1103/PhysRevLett.127.181802.

J. Brau et al.
Lycoris — A large-area, high resolution beam telescope.
Journal of Instrumentation, 16(10):P10023, and PUBDB-2022-00591, arXiv:2012.11495.
doi: 10.1088/1748-0221/16/10/P10023.

DEPFET, Belle-II and PXD Collaboration.
Commissioning and performance of the Belle II pixel detector.
Nuclear instruments & methods in physics research / A, 987:164875, and PUBDB-2022-00369.
doi: 10.1016/j.nima.2020.164875.

M. J. Dolan et al.
Erratum to: Revised constraints and Belle II sensitivity for visible and invisible axion-like particles.
Journal of high energy physics, 2021(3):190, and PUBDB-2022-00326, arXiv:1709.00009. DESY-17-127.
doi: 10.1007/JHEP03(2021)190.

M. Duerr et al.
Long-lived dark Higgs and inelastic dark matter at Belle II.
Journal of high energy physics, 2021(4):146, and PUBDB-2021-04493, DESY-20-226. arXiv:2012.08595.
doi: 10.1007/JHEP04(2021)146.

A. Ebrahimi et al.
Position reconstruction for segmented detectors.
Nuclear instruments & methods in physics research / A, 1014:165744, and PUBDB-2022-00516, arXiv:2107.06600.
doi: 10.1016/j.nima.2021.165744.

D. Guadagnoli, C. B. Park and F. Tenchini.
$\tau \to \ell+$ invisible through invisible-savvy collider variables.
Physics letters / B, 822:136701, and PUBDB-2022-00343, arXiv:2106.16236. CERN-TH-2021-101. LAPTH-023/21. CTPU-PTC-21-28.
doi: 10.1016/j.physletb.2021.136701.

S. Kurz.
Search for $B^+ \to K^+\nu\bar{\nu}$ and other electroweak/radiative penguin processes at Belle II.
2013612. European Physical Society conference on high energy physics 2021 - Online conference, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. 398:554 (1, and PUBDB-2021-05651.
SISSA, Trieste.
doi: 10.22323/1.398.0554.

LHeC Collaboration.
The Large Hadron-Electron Collider at the HL-LHC.
Journal of physics / G, 48(11):110501, and PUBDB-2022-00307, arXiv:2007.14491. CERN-ACC-Note-2020-0002. JLAB-ACP-20-3180.
doi: 10.1088/1361-6471/abf3ba.

Q. Liu et al.
Operational Experience and Performance of the Belle II Pixel Detector.
Journal of the Physical Society of Japan, 34:010002, and PUBDB-2021-05690.
doi: 10.7566/JPSCP.34.010002.

Y. Sato et al.
Monte Carlo matching in the Belle II software.
The European physical journal / Web of Conferences, 251:03021, and PUBDB-2021-05462.
doi: 10.1051/epjconf/202125103021.

SIMBA Collaboration.
Precision Global Determination of the $B \to X_s\gamma$ Decay Rate.
Physical review letters, 127(10):102001 (1, and PUBDB-2021-04284, arXiv:2007.04320. DESY-20-115. MIT-CTP 5220.
doi: 10.1103/PhysRevLett.127.102001.

Master Thesis

C. Ly.
Shower shape conversion between electrons and photons in Belle II using Cycle Generative Adversarial Network.
University of Hamburg, DESY-Hamburg, 2021.

S. Wermuth.
Neural Network based Pulse Shape Analysis with the Belle II Electromagnetic Calorimeter.
University of Hamburg, Hamburg, 2021.

Ph.D. Thesis

M. De Nuccio.
Search for Axion-Like Particles produced in e^+e^- collisions and photon energy resolution studies at Belle II.
University of Hamburg, 2021.

CMS

Published

N. A. Abdulov et al.
TMDlib2 and TMDplotter: a platform for 3D hadron structure studies.
The European physical journal / C, 81(8):752 (1, and PUBDB-2021-04874, arXiv:2103.09741. DESY-21-026. IFJPAN-IV-2021-4. JLAB-THY-21-3337.
doi: 10.1140/epjc/s10052-021-09508-8.

S. Amoroso et al.
Longitudinal Z-boson polarization and the Higgs boson production cross section at the Large Hadron Collider.
Physics letters / B, 821:136613, and PUBDB-2021-05680, arXiv:2012.10298.
doi: 10.1016/j.physletb.2021.136613.

S. Amoroso, D. Kar and M. Schott.
How to discover QCD Instantons at the LHC.
The European physical journal / C, 81(7):624, and PUBDB-2021-05682, arXiv:2012.09120.
doi: 10.1140/epjc/s10052-021-09412-1.

S. Baranov et al.
CASCADE3 A Monte Carlo event generator based on TMDs.
The European physical journal / C, 81(5):425, and PUBDB-2021-02542, arXiv:2101.10221. DESY-21-005.
doi: 10.1140/epjc/s10052-021-09203-8.

A. Bermudez Martinez, F. Hautmann and M. Mangano.
TMD evolution and multi-jet merging.
Physics letters / B, 822:136700 (1, and PUBDB-2021-04090, arXiv:2107.01224.
doi: 10.1016/j.physletb.2021.136700.

CMS Collaboration.
Angular analysis of the decay $B^+ \to K^*(892)^+\mu^+\mu^-$ in proton-proton collisions at $\sqrt{s} = 8$ TeV.
Journal of high energy physics, 04(4):124 (1, and PUBDB-2021-02219, arXiv:2010.13968. CMS-BPH-15-009. CERN-EP-2020-188.
doi: 10.1007/JHEP04(2021)124.

CMS Collaboration.
Combined searches for the production of supersymmetric top quark partners in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(11):970, and PUBDB-2021-05613, arXiv:2107.10892. CMS-SUS-20-002. CERN-EP-2021-120.
doi: 10.1140/epjc/s10052-021-09721-5.

CMS Collaboration.
Constraints on anomalous Higgs boson couplings to vector bosons and fermions in its production and decay using the four-lepton final state.
Physical review / D, 104(5):052004 (1, and PUBDB-2021-03984, arXiv:2104.12152. CERN-EP-2021-054. CMS-HIG-19-009.
doi: 10.1103/PhysRevD.104.052004.

CMS Collaboration.
Constraints on the Initial State of Pb-Pb Collisions via Measurements of Z-Boson Yields and Azimuthal Anisotropy at $\sqrt{s_{NN}}$=5.02 TeV.
Physical review letters, 127(10):102002 (1, and PUBDB-2021-03983, arXiv:2103.14089. CMS-HIN-19-003. CERN-EP-2021-039.
doi: 10.1103/PhysRevLett.127.102002.

CMS Collaboration.
Correlations of azimuthal anisotropy Fourier harmonics in pPb collisions at $\sqrt{s_{\mathrm{NN}}} = 8.16$ TeV.
Physical review / C, 103(1):014902, and PUBDB-2021-00702, arXiv:1905.09935. CMS-HIN-18-015. CERN-EP-2019-031.
doi: 10.1103/PhysRevC.103.014902.

CMS Collaboration.
Development and validation of HERWIG 7 tunes from CMS underlying-event measurements.
The European physical journal / C, 81(4):312, and PUBDB-2021-01838, arXiv:2011.03422. CMS-GEN-19-001. CERN-EP-2020-182.
doi: 10.1140/epjc/s10052-021-08949-5.

CMS Collaboration.
Electron and photon reconstruction and identification with the CMS experiment at the CERN LHC.
Journal of Instrumentation, 16(05):P05014, and PUBDB-2021-02949, arXiv:2012.06888. CMS-EGM-17-001. CERN-EP-2020-219.
doi: 10.1088/1748-0221/16/05/P05014.

CMS Collaboration.
Evidence for electroweak production of four charged leptons and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 812:135992 (1, and PUBDB-2020-05201, arXiv:2008.07013. CMS-SMP-20-001. CERN-EP-2020-127.
doi: 10.1016/j.physletb.2020.135992.

CMS Collaboration.
Evidence for Higgs boson decay to a pair of muons.
Journal of high energy physics, 01(1):148 (1, and PUBDB-2021-01028, arXiv:2009.04363. CMS-HIG-19-006. CERN-EP-2020-164.
doi: 10.1007/JHEP01(2021)148.

CMS Collaboration.
First measurement of large area jet transverse momentum spectra in heavy-ion collisions.
Journal of high energy physics, 05(5):284 (1, and PUBDB-2021-02944, arXiv:2102.13080. FERMILAB-PUB-21-160-CMS. CMS-HIN-18-014. CERN-EP-2020-226.
doi: 10.1007/JHEP05(2021)284.

CMS Collaboration.
First measurement of the cross section for top quark pair production with additional charm jets using dileptonic final states in pp collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 820:136565 (1, and PUBDB-2021-03525, arXiv:2012.09225. CMS-TOP-20-003. CERN-EP-2020-234.
doi: 10.1016/j.physletb.2021.136565.

CMS Collaboration.
In-medium modification of dijets in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
Journal of high energy physics, 05(5):116 (1, and PUBDB-2021-02939, arXiv:2101.04720. CMS-HIN-19-013. CERN-EP-2020-247.
doi: 10.1007/JHEP05(2021)116.

CMS Collaboration.
Measurement of b jet shapes in proton-proton collisions at $\sqrt{s} = 5.02$ TeV.
Journal of high energy physics, 05(5):054, and PUBDB-2021-02934, arXiv:2005.14219. CMS-HIN-18-020. CERN-EP-2020-060.
doi: 10.1007/JHEP05(2021)054.

CMS Collaboration.
Measurement of differential $t\bar{t}$ production cross sections in the full kinematic range using lepton+jets events from proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 104(9):092013, and PUBDB-2021-05608, arXiv:2108.02803. CMS-TOP-20-001. CERN-EP-2021-135.
doi: 10.1103/PhysRevD.104.092013.

CMS Collaboration.
Measurement of differential tt production cross sections using top quarks at large transverse momenta in pp collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 103(5):052008 (1, and PUBDB-2021-01685, arXiv:2008.07860. CMS-TOP-18-013. CERN-EP-2020-121.
doi: 10.1103/PhysRevD.103.052008.

CMS Collaboration.
Measurement of differential cross sections for Z bosons produced in association with charm jets in pp collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 04(4):109, and PUBDB-2021-02222, arXiv:2012.04119. CMS-SMP-19-011. CERN-EP-2020-206.
doi: 10.1007/JHEP04(2021)109.

CMS Collaboration.
Measurement of prompt open-charm production cross sections in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 11(11):225, and PUBDB-2021-05604, arXiv:2107.01476. CMS-BPH-18-003. CERN-EP-2021-085. arXiv:2107.01476. CMS-BPH-18-003. CERN-EP-2021-085.
doi: 10.1007/JHEP11(2021)225.

CMS Collaboration.
Measurement of the CP-violating phase ϕ_s in the $B^0_s \to J/\psi\,\phi(1020) \to \mu^+\mu^- K^+K^-$ channel in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 816:136188 (1, and PUBDB-2021-01684, arXiv:2007.02434. CMS-BPH-20-001. CERN-EP-2020-110.
doi: 10.1016/j.physletb.2021.136188.

CMS Collaboration.
Measurement of the azimuthal anisotropy of Υ(1S) and Υ(2S) mesons in PbPb collisions at $\sqrt{s_{NN}} = 5.02$ TeV.
Physics letters / B, 819:136385, and PUBDB-2021-02935, arXiv:2006.07707. CMS-HIN-19-002. CERN-EP-2020-039.
doi: 10.1016/j.physletb.2021.136385.

A. Cardini.
Measurement of the CP structure of the Yukawa interaction in Higgs boson decays to τ leptons.
1971347. 9th Large Hadron Collider Physics Conference, Paris (France), 7 Jun 2021 - 12 Jun 2021.
Proceedings of Science / International School for Advanced Studies, vol. (LHCP2021):209, and PUBDB-2022-00022. SISSA, Trieste.
doi: 10.22323/1.397.0209.

CMS Collaboration.
Measurement of the electroweak production of Zγ and two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV and constraints on anomalous quartic gauge couplings.
Physical review / D, 104(7):072001, and PUBDB-2021-05606, arXiv:2106.11082. CMS-SMP-20-016. CERN-EP-2021-095.
doi: 10.1103/PhysRevD.104.072001.

CMS Collaboration.
Measurement of the Higgs boson production rate in association with top quarks in final states with electrons, muons, and hadronically decaying tau leptons at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(4):378, and PUBDB-2021-02220, arXiv:2011.03652. CMS-HIG-19-008. CERN-EP-2020-200.
doi: 10.1140/epjc/s10052-021-09014-x.

CMS Collaboration.
Measurement of the inclusive and differential $t\bar{t}\gamma$ cross sections in the single-lepton channel and EFT interpretation at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 12(12):180, and PUBDB-2022-00236, arXiv:2107.01508. CMS-TOP-18-010. CERN-EP-2021-117.
doi: 10.1007/JHEP12(2021)180.

CMS Collaboration.
Measurement of the inclusive and differential Higgs boson production cross sections in the leptonic WW decay mode at $\sqrt{s} =$ 13 TeV.
Journal of high energy physics, 03:003, and PUBDB-2021-01403, arXiv:2007.01984. CMS-HIG-19-002. CERN-EP-2020-106.
doi: 10.1007/JHEP03(2021)003.

CMS Collaboration.
Measurement of the top quark mass using events with a single reconstructed top quark in pp collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 12(12):161, and PUBDB-2022-00239, arXiv:2108.10407. CMS-TOP-19-009. CERN-EP-2021-124.
doi: 10.1007/JHEP12(2021)161.

CMS Collaboration.
Measurement of the Wγ Production Cross Section in Proton-Proton Collisions at $\sqrt{s}$=13 TeV and Constraints on Effective Field Theory Coefficients.
Physical review letters, 126(25):252002 (1, and PUBDB-2021-02941, arXiv:2102.02283. CMS-SMP-19-002. CERN-EP-2021-008.
doi: 10.1103/PhysRevLett.126.252002.

CMS Collaboration.
Measurement of the Z boson differential production cross section using its invisible decay mode (Z$\nu\bar{\nu}$) in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 05(5):205, and PUBDB-2021-02938, arXiv:2012.09254. CMS-SMP-18-003. CERN-EP-2020-223.
doi: 10.1007/JHEP05(2021)205.

CMS Collaboration.
Measurements of $\mathrm{pp} \rightarrow \mathrm{ZZ}$ production cross sections and constraints on anomalous triple gauge couplings at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(3):200, and PUBDB-2021-01404, arXiv:2009.01186. CMS-SMP-19-001. CERN-EP-2020-145.
doi: 10.1140/epjc/s10052-020-08817-8.

CMS Collaboration.
Measurements of angular distance and momentum ratio distributions in three-jet and Z + two-jet final states in pp collisions.
The European physical journal / C, 81(9):852 (1, and PUBDB-2021-03980, arXiv:2102.08816. CMS-SMP-17-008. CERN-EP-2020-251.
doi: 10.1140/epjc/s10052-021-09570-2.

CMS Collaboration.
Measurements of Higgs boson production cross sections and couplings in the diphoton decay channel at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 07(7):27 (1, and PUBDB-2021-02948, arXiv:2103.06956. CMS-HIG-19-015. CERN-EP-2021-038.
doi: 10.1007/JHEP07(2021)027.

CMS Collaboration.
Measurements of production cross sections of polarized same-sign W boson pairs in association with two jets in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 812:136018, and PUBDB-2021-00721, arXiv:2009.09429. CMS-SMP-20-006. CERN-EP-2020-168.
doi: 10.1016/j.physletb.2020.136018.

CMS Collaboration.
Measurements of production cross sections of the Higgs boson in the four-lepton final state in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(6):488 (1, and PUBDB-2021-02946, arXiv:2103.04956. CMS-HIG-19-001. CERN-EP-2021-016.
doi: 10.1140/epjc/s10052-021-09200-x.

CMS Collaboration.
Measurements of the differential cross sections of the production of Z + jets and γ + jets and of Z boson emission collinear with a jet in pp collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 05(5):285 (1, and PUBDB-2021-02940, arXiv:2102.02238. CMS-SMP-19-010. CERN-EP-2020-250.
doi: 10.1007/JHEP05(2021)285.

CMS Collaboration.
Measurements of the Electroweak Diboson Production Cross Sections in Proton-Proton Collisions at $\sqrt{s} = 5.02$ TeV Using Leptonic Decays.
Physical review letters, 127(19):191801, and PUBDB-2021-05605, arXiv:2107.01137. CMS-SMP-20-012. CERN-EP-2021-111. arXiv:2107.01137. CMS-SMP-20-012. CERN-EP-2021-111. arXiv:2107.01137. CMS-SMP-20-012. CERN-EP-2021-111.
doi: 10.1103/PhysRevLett.127.191801.

CMS Collaboration.
Measurements of the pp $\rightarrow$ W$^{\pm}\gamma\gamma$ and pp $\rightarrow$ Z$\gamma\gamma$ cross sections at $\sqrt{s} = 13$ TeV and limits on anomalous quartic gauge couplings.
Journal of high energy physics, 10(10):174, and PUBDB-2021-05602, arXiv:2105.12780. CMS-SMP-19-013. CERN-EP-2021-073. arXiv:2105.12780. CMS-SMP-19-013. CERN-EP-2021-073.
doi: 10.1007/JHEP10(2021)174.

CMS Collaboration.
MUSiC: a model-unspecific search for new physics in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(7):629 (1, and PUBDB-2021-03522, arXiv:2010.02984. CMS-EXO-19-008. CERN-EP-2020-171.
doi: 10.1140/epjc/s10052-021-09236-z.

CMS Collaboration.
Observation of a New Excited Beauty Strange Baryon Decaying to $\Xi_b^- \pi^+ \pi^-$.
Physical review letters, 126(25):252003 (1, and PUBDB-2021-02942, arXiv:2102.04524. CMS-BPH-20-004. CERN-EP-2021-020.
doi: 10.1103/PhysRevLett.126.252003.

CMS Collaboration.
Observation of Forward Neutron Multiplicity Dependence of Dimuon Acoplanarity in Ultraperipheral Pb-Pb Collisions at $\sqrt{s_{NN}}$=5.02 TeV.
Physical review letters, 127(12):122001 (1, and PUBDB-2021-03978, arXiv:2011.05239. CMS-HIN-19-014. CERN-EP-2020-196.
doi: 10.1103/PhysRevLett.127.122001.

CMS Collaboration.
Observation of tW production in the single-lepton channel in pp collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 11(11):111, and PUBDB-2021-05614, arXiv:2109.01706. CMS-TOP-20-002. CERN-EP-2021-131.
doi: 10.1007/JHEP11(2021)111.

CMS Collaboration.
Performance of the CMS muon trigger system in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of Instrumentation, 16(07):P07001 (1, and PUBDB-2021-02950, arXiv:2102.04790. CMS-MUO-19-001. CERN-EP-2021-013.
doi: 10.1088/1748-0221/16/07/P07001.

CMS Collaboration.
Precision luminosity measurement in proton-proton collisions at $\sqrt{s} = 13$ TeV in 2015 and 2016 at CMS.
The European physical journal / C, 81(9):800 (1, and PUBDB-2021-03982, arXiv:2104.01927. CMS-LUM-17-003. CERN-EP-2021-033.
doi: 10.1140/epjc/s10052-021-09538-2.

J. Knolle.
Precision luminosity measurement with proton-protoncollisions at the CMS experiment in Run 2.
Proceedings of Science. 40th International Conference on High Energy Physics, ONLINE (Virtual World), 28 Jul 2020 - 6 Aug 2020.
Proceedings of Science / International School for Advanced Studies, vol. (ICHEP2020):748, and PUBDB-2021-00724. SISSA, Trieste.
doi: 10.3204/PUBDB-2021-00724.

CMS Collaboration.
Probing effective field theory operators in the associated production of top quarks with a Z boson in multilepton final states at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 12(12):083, and PUBDB-2021-05609, arXiv:2107.13896. CMS-TOP-21-001. CERN-PH-2021-126.
doi: 10.1007/JHEP12(2021)083.

CMS Collaboration.
Search for a heavy Higgs boson decaying into two lighter Higgs bosons in the $\tau\tau$bb final state at 13 TeV.
Journal of high energy physics, 11(11):057, and PUBDB-2021-05607, arXiv:2106.10361. CMS-HIG-20-014. CERN-EP-2021-094.
doi: 10.1007/JHEP11(2021)057.

CMS Collaboration.
Search for a heavy resonance decaying to a top quark and a W boson at $\sqrt{s} = 13$ TeV in the fully hadronic final state.
Journal of high energy physics, 12(12):106, and PUBDB-2021-05603, arXiv:2104.12853. CMS-B2G-19-003. CERN-EP-2021-044. arXiv:2104.12853. CMS-B2G-19-003. CERN-EP-2021-044.
doi: 10.1007/JHEP12(2021)106.

CMS Collaboration.
Search for charged Higgs bosons produced in vector boson fusion processes and decaying into vector boson pairs in proton–proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(8):723 (1, and PUBDB-2021-03529, arXiv:2104.04762. CMS-HIG-20-017. CERN-EP-2021-045.
doi: 10.1140/epjc/s10052-021-09472-3.

CMS Collaboration.
Search for chargino-neutralino production in events with Higgs and W bosons using 137 fb^{-1} of proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 10(10):045, and PUBDB-2021-05611, arXiv:2107.12553. CMS-SUS-20-003. CERN-EP-2021-114.
doi: 10.1007/JHEP10(2021)045.

CMS Collaboration.
Search for dark matter produced in association with a leptonically decaying Z boson in proton-proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(1):13, and PUBDB-2021-00707, arXiv:2008.04735. CMS-EXO-19-003. CERN-EP-2020-136.
doi: 10.1140/epjc/s10052-020-08739-5.

CMS Collaboration.
Search for dark photons in Higgs boson production via vector boson fusion in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 03(3):11 (1, and PUBDB-2021-01687, arXiv:2009.14009. CMS-EXO-20-005. CERN-EP-2020-173.
doi: 10.1007/JHEP03(2021)011.

CMS Collaboration.
Search for lepton-flavor violating decays of the Higgs boson in the $\mu\tau$ and eτ final states in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review / D, 104(3):032013 (1, and PUBDB-2021-03987, arXiv:2105.03007. CMS-HIG-20-009. CERN-EP-2021-061.
doi: 10.1103/PhysRevD.104.032013.

CMS Collaboration.
Search for long-lived particles decaying in the CMS endcap muon detectors in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review letters, 127(26):261804, and PUBDB-2022-00238, arXiv:2107.04838. CMS-EXO-20-015. CERN-EP-2021-125.
doi: 10.1103/PhysRevLett.127.261804.

CMS Collaboration.
Search for long-lived particles decaying to jets with displaced vertices in proton-proton collisions at $\sqrt{s}$ =13 TeV.
Physical review / D, 104(5):052011 (1, and PUBDB-2021-03986, arXiv:2104.13474. CMS-EXO-19-013. CERN-EP-2021-052.
doi: 10.1103/PhysRevD.104.052011.

CMS Collaboration.
Search for long-lived particles using displaced jets in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 104(1):012015 (1, and PUBDB-2021-03524, arXiv:2012.01581. CMS-EXO-19-021. CERN-EP-2020-202.
doi: 10.1103/PhysRevD.104.012015.

CMS Collaboration.
Search for new particles in events with energetic jets and large missing transverse momentum in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 11(11):153, and PUBDB-2021-05610, arXiv:2107.13021. CMS-EXO-20-004. CERN-EP-2021-136.
doi: 10.1007/JHEP11(2021)153.

CMS Collaboration.
Search for new physics in top quark production with additional leptons in proton-proton collisions at $\sqrt{s} = 13$ TeV using effective field theory.
Journal of high energy physics, 03(3):95 (1, and PUBDB-2021-01689, arXiv:2012.04120. CMS-TOP-19-001. CERN-EP-2020-211.
doi: 10.1007/JHEP03(2021)095.

CMS Collaboration.
Search for nonresonant Higgs boson pair production in final states with two bottom quarks and two photons in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 03(3):257, and PUBDB-2021-02221, arXiv:2011.12373. CMS-HIG-19-018. CERN-EP-2020-222.
doi: 10.1007/JHEP03(2021)257.

CMS Collaboration.
Search for resonant and nonresonant new phenomena in high-mass dilepton final states at $\sqrt{s}$ = 13 TeV.
Journal of high energy physics, 07(7):208, and PUBDB-2021-03528, arXiv:2103.02708. CMS-EXO-19-019. CERN-EP-2021-026.
doi: 10.1007/JHEP07(2021)208.

CMS Collaboration.
Search for singly and pair-produced leptoquarks coupling to third-generation fermions in proton-proton collisions at $\sqrt{s} =$ 13 TeV.
Physics letters / B, 819:136446, and PUBDB-2021-02937, arXiv:2012.04178. CMS-EXO-19-015. CERN-EP-2020-216.
doi: 10.1016/j.physletb.2021.136446.

CMS Collaboration.
Search for supersymmetry in final states with two oppositely charged same-flavor leptons and missing transverse momentum in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 04(4):123, and PUBDB-2021-02223, arXiv:2012.08600. CMS-SUS-20-001. CERN-EP-2020-231.
doi: 10.1007/JHEP04(2021)123.

CMS Collaboration.
Search for the lepton flavor violating decay $\tau \to 3\mu$ in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Journal of high energy physics, 01(1):163 (1, and PUBDB-2021-01026, arXiv:2007.05658. CMS-BPH-17-004. CERN-EP-2020-113.
doi: 10.1007/JHEP01(2021)163.

CMS Collaboration.
Search for the rare decay of the W boson into a pion and a photon in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physics letters / B, 819:136409, and PUBDB-2021-02936, arXiv:2011.06028. CMS-SMP-20-008. CERN-EP-2020-197.
doi: 10.1016/j.physletb.2021.136409.

CMS Collaboration.
Search for top squark pair production using dilepton final states in pp collision data collected at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(1):3, and PUBDB-2021-00708, arXiv:2008.05936. CMS-SUS-19-011. CERN-EP-2020-131.
doi: 10.1140/epjc/s10052-020-08701-5.

CMS Collaboration.
Search for top squark production in fully-hadronic final states in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 104(5):052001 (1, and PUBDB-2021-03981, arXiv:2103.01290. CMS-SUS-19-010. CERN-EP-2021-022.
doi: 10.1103/PhysRevD.104.052001.

CMS Collaboration.
Search for top squarks in final states with two top quarks and several light-flavor jets in proton-proton collisions at $\sqrt{s}$ = 13 TeV.
Physical review / D, 104(3):032006 (1, and PUBDB-2021-03526, arXiv:2102.06976. CMS-SUS-19-004. CERN-

EP-2021-015.
doi: 10.1103/PhysRevD.104.032006.

CMS Collaboration.
Search for W′ bosons decaying to a top and a bottom quark at $\sqrt{s} = 13$ TeV in the hadronic final state.
Physics letters / B, 820:136535 (1, and PUBDB-2021-03532, arXiv:2104.04831. CMS-B2G-20-005. CERN-EP-2021-049.
doi: 10.1016/j.physletb.2021.136535.

CMS Collaboration.
Studies of charm and beauty hadron long-range correlations in pp and pPb collisions at LHC energies.
Physics letters / B, 813:136036 (1, and PUBDB-2021-00719, arXiv:2009.07065. CMS-HIN-19-009. CERN-EP-2020-141.
doi: 10.1016/j.physletb.2020.136036.

CMS Collaboration.
Study of Drell-Yan dimuon production in proton-lead collisions at $\sqrt{s_{NN}} = 8.16$ TeV.
Journal of high energy physics, 05(5):182 (1, and PUBDB-2021-02945, arXiv:2102.13648. CMS-HIN-18-003. CERN-EP-2021-028.
doi: 10.1007/JHEP05(2021)182.

CMS Collaboration.
Study of Z boson plus jets events using variables sensitive to double-parton scattering in pp collisions at 13 TeV.
Journal of high energy physics, 10(10):176, and PUBDB-2021-05601, arXiv:2105.14511. CMS-SMP-20-009. CERN-EP-2021-091. arXiv:2105.14511. CMS-SMP-20-009. CERN-EP-2021-091.
doi: 10.1007/JHEP10(2021)176.

A. Cardini.
Tau identification exploiting deep learning techniques.
Proceedings of Science. 40th International Conference on High Energy Physics, ONLINE (Virtual World), 28 Jul 2020 - 6 Aug 2020.
Proceedings of Science / International School for Advanced Studies, vol. (ICHEP2020):723, and PUBDB-2021-00725.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-00725.

CMS Collaboration.
The very forward CASTOR calorimeter of the CMS experiment.
Journal of Instrumentation, 16(02):P02010 (1, and PUBDB-2021-01691, arXiv:2011.01185. CMS-PRF-18-002. CERN-EP-2020-180.
doi: 10.1088/1748-0221/16/02/P02010.

P. Connor.
Tracker alignment of the CMS detector.
Proceedings of Science. 40th International Conference on High Energy Physics, ONLINE (Virtual World), 28 Jul 2020 - 6 Aug 2020.
Proceedings of Science / International School for Advanced Studies, vol. (ICHEP2020):729, and PUBDB-2021-00726.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-00726.

CMS Collaboration and TOTEM Collaboration.
Erratum to: Measurement of single-diffractive dijet production in proton–proton collisions at $\sqrt{s} = 8$ TeV with the CMS and TOTEM experiments.
The European physical journal / C, 81(5):383, and PUBDB-2022-00252, arXiv:2002.12146. CMS-FSQ-12-033. TOTEM-2020-001. CERN-EP-2019-260.
doi: 10.1140/epjc/s10052-021-08863-w.

CMS HGCAL Collaboration.
The DAQ system of the 12,000 channel CMS high granularity calorimeter prototype.
Journal of Instrumentation, 16(04):T04001, and PUBDB-2022-00281, arXiv:2012.03876.
doi: 10.1088/1748-0221/16/04/T04001.

CMS Tracker Collaboration.
The CMS Phase-1 Pixel Detector Upgrade.
Journal of Instrumentation, 16(02):P02027, and PUBDB-2022-00361, arXiv:2012.14304.
doi: 10.1088/1748-0221/16/02/P02027.

D0 Collaboration.
Study of the normalized transverse momentum distribution of W bosons produced in $p\bar{p}$ collisions at $\sqrt{s} = 1.96$ TeV.
Physical review / D, 103(1):012003, and PUBDB-2021-05541, arXiv:2007.13504. FERMILAB-PUB-20-354-E.
doi: 10.1103/PhysRevD.103.012003.

R. Escribano et al.
On Broad Kaluza-Klein Gluons.
Journal of high energy physics, 05(5):121, and PUBDB-2022-00409, arXiv:2102.11241.
doi: 10.1007/JHEP05(2021)121.

H. Jung, S. Taheri Monfared and T. Wening.
Determination of collinear and TMD photon densities using the Parton Branching method.
Physics letters / B, 817:136299, and PUBDB-2021-02116, arXiv:2102.01494. DESY-21-014.
doi: 10.1016/j.physletb.2021.136299.

LHeC Collaboration.
The Large Hadron-Electron Collider at the HL-LHC.
Journal of physics / G, 48(11):110501, and PUBDB-2022-00307, arXiv:2007.14491. CERN-ACC-Note-2020-0002. JLAB-ACP-20-3180.
doi: 10.1088/1361-6471/abf3ba.

F. Rehm et al.
Physics Validation of Novel Convolutional 2D Architectures for Speeding Up High Energy Physics Simulations.
25th International Conference on Computing in High-Energy and Nuclear Physics, Online (France), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03042 (1, and PUBDB-2021-04102, arXiv:2105.08960.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103042.

A. M. Sirunyan et al.
Measurement of prompt D^0 and $\overline{\mathrm{D}}^0$ meson azimuthal anisotropy and search for strong electric fields in PbPb collisions at $\sqrt{s_{\mathrm{NN}}} =$ 5.02 TeV.
Physics letters / B, 816:136253 (1, and PUBDB-2021-01686, arXiv:2009.12628. CMS-HIN-19-008. CERN-EP-2020-155.
doi: 10.1016/j.physletb.2021.136253.

A. M. Sirunyan et al.
Search for a heavy vector resonance decaying to a Z boson and a Higgs boson in proton-proton collisions at $\sqrt{s} = 13$ TeV.
The European physical journal / C, 81(8):688 (1, and PUBDB-2021-03527, arXiv:2102.08198. CMS-B2G-19-006. CERN-EP-2021-009.
doi: 10.1140/epjc/s10052-021-09348-6.

The CMS HGCAL collaboration.
Construction and commissioning of CMS CE prototype silicon modules.
Journal of Instrumentation, 16(04):T04002, and PUBDB-2022-00282, arXiv:2012.06336.
doi: 10.1088/1748-0221/16/04/T04002.

TOTEM Collaboration and CMS Collaboration.
Hard color-singlet exchange in dijet events in proton-proton collisions at $\sqrt{s} = 13$ TeV.
Physical review / D, 104(3):032009 (1, and PUBDB-2021-03979, arXiv:2102.06945. CMS-SMP-19-006. TOTEM-2021-001. CERN-EP-2020-229.
doi: 10.1103/PhysRevD.104.032009.

xfitter Developers' Collaboration.
QCD analysis of pion fragmentation functions in the xFitter framework.
Physical review / D, 104(5):056019, and PUBDB-2021-05679, arXiv:2105.11306.
doi: 10.1103/PhysRevD.104.056019.

Master Thesis

M. Bayat Makou.
Optimizing the Machine Learning techniques in the $H \to \tau\tau$ analysis with CMS data.
Universität Hamburg, Hamburg, 2021.

Ph.D. Thesis

J. P. Asmuss.
Search for high-mass bosons of an extended Higgs sector in b quark final states using the 2017 data set of the CMS experiment.
Universität Hamburg, Hamburg, 2021.

A. Cardini.
Measurement of the CP properties of the Higgs boson in its decays to τ leptons with the CMS experiment.
Universität Hamburg, 2021.

A. Mohamed.
Search for Dark Matter with machine learning techniques in leptonic final states and missing transverse energy at the CMS Experiment.
RWTH Aachen Universität, Hamburg, 2021.

A. Saibel.
Phenomenology of $t\bar{t}H$ Production with Top Quark Running Mass and the Differential Cross-Section Measurement of $t\bar{t}+b$-jets Production in the Dilepton Channel at $\sqrt{s} = 13$ TeV with the CMS Experiment.
Universität Hamburg, Hamburg, 2021.

R. E. Sosa Ricardo.
Measurement of multi-differential cross sections for the production of top quark pairs plus additional jets in pp collisions at √s = 13 TeV.
Universität Hamburg, Hamburg, 2021.

Electronics Development

Published

A.-L. Poley et al.
Mapping the material distribution of a complex structure in an electron beam.
Journal of Instrumentation, 16(01):P01010, and PUBDB-2021-00508, arXiv:2105.10128.
doi: 10.1088/1748-0221/16/01/P01010.

M. Porro et al.
The MiniSDD-Based 1-Mpixel Camera of the DSSC Project for the European XFEL.
IEEE transactions on nuclear science, 68(6):1334, and PUBDB-2021-04780.
doi: 10.1109/TNS.2021.3076602.

Master Thesis

A. Chauhan.
Design of an Analog Time-Variant Filter for X-Ray Pixel Detector Readout in CMOS Technology.
TU Hamburg-Harburg, 2021.

FTX

Published

H. Abramowicz et al.
Conceptual Design Report for the LUXE Experiment.
European physical journal special topics, 230(11):2445, and PUBDB-2021-00893, arXiv:2102.02032. DESY-21-016.
doi: 10.1140/epjs/s11734-021-00249-z.

M. Aleksa et al.
Calorimetry at FCC-ee.
The European physical journal / Plus, 136(10):1066, and PUBDB-2021-05657, arXiv:2109.00391.
doi: 10.1140/epjp/s13360-021-02034-2.

C. M. Berggren.
New physics searches with the International Large Detector at the ILC.
The European Physical Society Conference on High Energy Physics, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):713, and PUBDB-2021-03998.
SISSA, Trieste.
doi: 10.22323/1.398.0730.

C. M. Berggren et al.
Kinematic edge detection using finite impulse response filters.
Nuclear instruments & methods in physics research / A, 1010:165555 (1, and PUBDB-2021-03076, DESY-20-233. ILD-PHYS-2020-003. arXiv:2012.11415.
doi: 10.1016/j.nima.2021.165555.

J. Brau et al.
Lycoris — A large-area, high resolution beam telescope.
Journal of Instrumentation, 16(10):P10023, and PUBDB-2022-00591, arXiv:2012.11495.
doi: 10.1088/1748-0221/16/10/P10023.

E. Buhmann et al.
Decoding Photons: Physics in the Latent Space of a BIB-AE Generative Network.
25th International Conference on Computing in High-Energy and Nuclear Physics, Online (Online), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03003, and PUBDB-2021-04961, arXiv:2102.12491. DESY-21-029.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103003.

U. Einhaus.
Charged Hadron Identification with dE/dx and Time-of-Flight at Future Higgs Factories.
1994612. The European Physical Society Conference on High Energy Physics, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):760, and PUBDB-2021-04012, arXiv:2112.10009. ILD-PHYS-PROC–2021-015.
SISSA, Trieste.
doi: 10.22323/1.398.0760.

P. Fernandez Declara et al.
Key4hep - Turnkey Software for Future Colliders.
8. Cracow Epiphany Conference on Future of Particle Physics, Cracow (Poland), 7 Jan 2021 - 10 Jan 2021.
Acta physica Polonica / B, vol. 528:1031, and PUBDB-2021-04005.
Inst. of Physics, Jagellonian Univ., Cracow.
doi: 10.5506/APhysPolB.52.1031.

P. Fernandez Declara et al.
Key4hep: Status and Plans.
25th International Conference on Computing in High-Energy and Nucelar Physics, Hamburg (Germany), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03025, and PUBDB-2021-04007.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103025.

M. Frank et al.
CAD support and new developments in DD4hep.
25th International Conference on Computing in High-Energy and Nucelar Physics, CERN (Switzerland), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03015, and PUBDB-2021-05343.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103015.

F. Gaede et al.
EDM4hep and podio - The event data model of the Key4hep project and its implementation.
25th International Conference on Computing in High-Energy and Nucelar Physics, Hamburg (Germany), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03026, and PUBDB-2021-04010.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103026.

Group, Particle Data.
Review of Particle Physics and 2021 Update.
Progress of theoretical and experimental physics, 2020(8):083C01, and PUBDB-2021-05664.
doi: 10.1093/ptep/ptaa104.

B. Kettle et al.
A laser–plasma platform for photon–photon physics: the two photon Breit–Wheeler process.
New journal of physics, 23(11):115006, and PUBDB-2021-02828.
doi: 10.1088/1367-2630/ac3048.

M. Kirchen et al.
Optimal Beam Loading in a Laser-Plasma Accelerator.
Physical review letters, 126:174801, and PUBDB-2021-01303.
doi: 10.1103/PhysRevLett.126.174801.

A. Knetsch et al.
Stable witness-beam formation in a beam-driven plasma cathode.
Physical review accelerators and beams, 24(10):101302, and PUBDB-2021-02678, arXiv:2007.12639. DESY-20-125.
doi: 10.1103/PhysRevAccelBeams.24.101302.

C. A. Lindstroem.
Staging of plasma-wakefield accelerators.
Physical review accelerators and beams, 24(1):014801, and PUBDB-2021-04448, DESY-21-001. arXiv:2007.05258.
doi: 10.1103/PhysRevAccelBeams.24.014801.

C. A. Lindstroem et al.
Energy-spread preservation and high efficiency in a plasma-wakefield accelerator.
Physical review letters, 126(1):014801 (1, and PUBDB-2020-04955.
doi: 10.1103/PhysRevLett.126.014801.

M. Borysova.
Studies of high-field QED with the LUXE experiment at theEuropean XFEL.
12. 22d International Workshop on Radiation Imaging Detectors, Ghent (Belgium), 27 Jun 2021 - 1 Jul 2021.
Journal of Instrumentation, vol. 1612:C12030, and PUBDB-2021-03858, arXiv:2110.15892.
Inst. of Physics, London.
doi: 10.1088/1748-0221/16/12/C12030.

B. Marchetti et al.
Experimental Demonstration of Novel Beam Characterization using a Polarizable X-Band Transverse Deflection Structure.
Scientific reports, 11(1):3560, and PUBDB-2021-00947.
doi: 10.1038/s41598-021-82687-2.

R. M. Nazhmudinov et al.
K-Shell Ionization Cross Section of Ti and Cu Atoms by 1 and 2 GeV Electrons.
Journal of physics / B, 54(4):045201 (1, and PUBDB-2021-02984.
doi: 10.1088/1361-6455/abd961.

Y. Radkhorrami and J. List.
Kinematic Fitting for Particle Flow Detectors at Future Higgs Factories.
Particles and Nuclei International Conference, Lisbon (Portugal), 5 Sep 2021 - 10 Sep 2021.
Proceedings of Science / International School for Advanced Studies, vol. (PANIC2021):4, and PUBDB-2021-04489, DESY-21-195. arXiv:2111.14775.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-04489.

Y. Radkhorrami and J. List.
Kinematic Fitting for ParticleFlow Detectors at Future Higgs Factories.
1952245. The European Physical Society Conference on High Energy Physics, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):761, and PUBDB-2021-03991, DESY-21-157. arXiv:2110.13731. ILD-PHYS-PROC–2021-010.
SISSA, Trieste.
doi: 10.22323/1.398.0761.

K. N. Sjobak et al.
Strong focusing gradient in a linear active plasma lens.
Physical review accelerators and beams, 24(12):121306, and PUBDB-2021-03811, arXiv:2012.10680.
doi: 10.1103/PhysRevAccelBeams.24.121306.

K. Svendsen et al.
A focused very high energy electron beam for fractionated stereotactic radiotherapy.
Scientific reports, 11(1):5844, and PUBDB-2022-00261.
doi: 10.1038/s41598-021-85451-8.

V. Volkl et al.
Building HEP Software with Spack: Experiences from Pilot Builds for Key4hep and Outlook for LCG Releases.
25th International Conference on Computing in High-Energy and Nucelar Physics, Hamburg (Germany), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:03056, and PUBDB-2021-04011.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125103056.

Ph.D. Thesis

N. M. Lockmann.
Noninvasive Measurements of Electron Bunch Current Profiles with Few-Femtosecond Resolution at MHz Repetition Rates.
Universität Hamburg, Hamburg, 2021.

S. Schröder.
External injection of electron beams into plasma-wakefield accelerators.
Universität Hamburg, Hamburg, 2021.

H1

Published

H1 Collaboration.
Erratum to: Determination of the strong coupling constant $\alpha_s(m_Z)$ in next-to-next-to-leading order QCD using H1 jet cross section measurements.
The European physical journal / C, 81(8):738, and PUBDB-2022-00678, arXiv:1709.07251. DESY-17-137.
doi: 10.1140/epjc/s10052-021-09394-0.

H1 Collaboration.
Erratum to: Measurement of jet production cross sections in deep-inelastic ep scattering at HERA.
The European physical journal / C, 81(8):739, and PUBDB-2022-00661, arXiv:1611.03421. DESY-16-200.
doi: 10.1140/epjc/s10052-021-09370-8.

H1 Collaboration.
Measurement of charged particle multiplicity distributions in DIS at HERA and its implication to entanglement entropy of partons.
The European physical journal / C, 81(3):212 (1, and PUBDB-2021-01478, DESY-20-176. arXiv:2011.01812.
doi: 10.1140/epjc/s10052-021-08896-1.

Z. Tu.
HERA data on azimuthal decorrelation and charged particle multiplicity spectra probing QCD dynamics and quantum entanglement effects.
1828482. 40th International Conference on High Energy Physics, Prague (virtual meeting), 28 Jul 2020 - 6 Aug 2020.
Proceedings of Science / International School for Advanced Studies, vol. 390:1, and PUBDB-2021-02154, arXiv:2011.02875.
SISSA, Trieste.
doi: 10.22323/1.390.0513.

IT

Published

S. Günther et al.
X-ray screening identifies active site and allosteric inhibitors of SARS-CoV-2 main protease.
Science / Science now, x:eabf7945 (1, and PUBDB-2021-01692.
doi: 10.1126/science.abf7945.

J. K. Keppler et al.
Towards recombinantly produced milk proteins: Physicochemical and emulsifying properties of engineered whey protein beta-lactoglobulin variants.
Food hydrocolloids, 110:106132, and PUBDB-2022-00366.
doi: 10.1016/j.foodhyd.2020.106132.

L. Morschel et al.
Improving Performance of Tape Restore Request Scheduling in the Storage System dCache; 25th ed.
25th International Conference on Computing in High-Energy and Nuclear Physics, virtual (virtual), 17 May 2021 - 21 May 2021.
The European physical journal / Web of Conferences, vol. 251:02016, and PUBDB-2021-02673.
EDP Sciences, Les Ulis.
doi: 10.1051/epjconf/202125102016.

OLYMPUS

Published

Olympus Collaboration.
Measurement of the Charge-Averaged Elastic Lepton-Proton Scattering Cross Section by the OLYMPUS Experiment.
Physical review letters, 126(16):162501 (1, and PUBDB-2021-02115, arXiv:2008.05349. DESY-20-132.
doi: 10.1103/PhysRevLett.126.162501.

Theory

Published

J. Ablinger, J. Blümlein and C. Schneider.
Iterated integrals over letters induced by quadratic forms.
Physical review / D, 103(9):096025 (1, and PUBDB-2021-02963, DESY-21-031. DO–TH 21/05. RISC-Linz Report Series No. 21-05. SAGEX-21-05. arXiv:2103.08330.
doi: 10.1103/PhysRevD.103.096025.

N. Aggarwal et al.
Challenges and opportunities of gravitational-wave searches at MHz to GHz frequencies.
Living reviews in relativity, 24(1):4, and PUBDB-2022-00101, arXiv:2011.12414. CERN-TH-2020-185. HIP-2020-28/TH. DESY-20-195.
doi: 10.1007/s41114-021-00032-5.

P. Agrawal et al.
Feebly-interacting particles: FIPs 2020 workshop report.
The European physical journal / C, 81(11):1015, and PUBDB-2022-00284, arXiv:2102.12143.
doi: 10.1140/epjc/s10052-021-09703-7.

J. J. Aguilera-Verdugo et al.
Mathematical properties of nested residues and their application to multi-loop scattering amplitudes.
Journal of high energy physics, 02(2):112, and PUBDB-2022-00183, arXiv:2010.12971. IFIC/20-30. DESY-20-172. MPP-2020-184.
doi: 10.1007/JHEP02(2021)112.

F. Alday et al.
The Pollica perspective on the (super)-conformal world.
Journal of physics / A, 54(30):303001, and PUBDB-2021-05519.
doi: 10.1088/1751-8121/abf38e.

C. Alexandrou et al.
Quark flavor decomposition of the nucleon axial form factors.
Physical review / D, 104(7):074503, and PUBDB-2021-03000, arXiv:2106.13468.
doi: 10.1103/PhysRevD.104.074503.

C. Alexandrou et al.
Flavor decomposition for the proton helicity parton distribution functions.
Physical review letters, 126(10):102003, and PUBDB-2021-04681, arXiv:2009.13061. DESY-20-207.
doi: 10.1103/PhysRevLett.126.102003.

C. Alexandrou et al.
Flavor decomposition of the nucleon unpolarized, helicity and transversity parton distribution functions from lattice QCD simulations.
Physical review / D, 104(5):054503, and PUBDB-2021-03001, arXiv:2106.16065.
doi: 10.1103/PhysRevD.104.054503.

C. Alexandrou et al.
Lattice continuum-limit study of nucleon quasi-PDFs.
Physical review / D, 103(9):094512, and PUBDB-2021-04955, arXiv:2011.00964. CERN-TH-2020-181. DESY-20-208.
doi: 10.1103/PhysRevD.103.094512.

J. R. Andersen et al.
Combined subleading high-energy logarithms and NLO accuracy for W production in association with multiple jets.
Journal of high energy physics, 04(4):105, and PUBDB-2022-00592, arXiv:2012.10310. DESY-20-233. DCPT/20/134. IPPP/20/67. MCnet-20-27. SAGEX-20-28.
doi: 10.1007/JHEP04(2021)105.

J. R. Andersen et al.
Logarithmic corrections to the QCD component of same-sign W-pair production for vector boson scattering studies.
Physical review / D, 104(11):114008, and PUBDB-2021-05278, arXiv:2107.06818. DCPT/21/14. DESY-21-107. IPPP/21/07. MCnet-21-13. SAGEX-21-16.
doi: 10.1103/PhysRevD.104.114008.

H. Bahl, N. Murphy and H. Rzehak.
Hybrid calculation of the MSSM Higgs boson masses using the complex THDM as EFT.
The European physical journal / C, 81(2):128, and PUBDB-2022-00381, arXiv:2010.04711. DESY-20-155.
doi: 10.1140/epjc/s10052-021-08939-7.

H. Bahl and I. Sobolev.
Two-loop matching of renormalizable operators: general considerations and applications.
Journal of high energy physics, 03(3):286, and PUBDB-2021-01961, arXiv:2010.01989. DESY-20-153.
doi: 10.1007/JHEP03(2021)286.

H. Bahl, T. Stefaniak and J. Wittbrodt.
The forgotten channels: charged Higgs boson decays to a $W^{\pm}$ and a non-SM-like Higgs boson.
Journal of high energy physics, 06(6):183 (1, and PUBDB-2021-03153, arXiv:2103.07484. DESY-21-035. LU TP 21-09.
doi: 10.1007/JHEP06(2021)183.

I. Baldes, Y. Gouttenoire and F. Sala.
String Fragmentation in Supercooled Confinement and Implications for Dark Matter.
Journal of high energy physics, 04(4):278, and PUBDB-2021-02424, arXiv:2007.08440. DESY-20-122. ULB-TH/20-08.
doi: 10.1007/JHEP04(2021)278.

G. S. Bali et al.
Double parton distributions in the nucleon from lattice QCD.
Journal of high energy physics, 09(9):106 (1, and PUBDB-2022-00068, arXiv:2106.03451. DESY-21-066.
doi: 10.1007/JHEP09(2021)106.

G. S. Bali et al.
Double parton distributions in the pion from lattice QCD.
Journal of high energy physics, 02(2):67, and PUBDB-2021-01101, arXiv:2006.14826. DESY-20-098. CERN-TH-2020-086.
doi: 10.1007/JHEP02(2021)067.

G. Ballesteros et al.
Revisiting isocurvature bounds in models unifying the axion with the inflaton.
Journal of cosmology and astroparticle physics, 2021(09):036 (1, and PUBDB-2021-04107, arXiv:2104.13847. IFT-UAM/CSIC-21-45. DESY-21-048. TUM-HEP-1334-21.
doi: 10.1088/1475-7516/2021/09/036.

J. Barrat, P. Liendo and J. Plefka.
Two-Point Correlator of Chiral Primary Operators with a Wilson Line Defect in $\mathcal{N} = 4$ SYM.
Journal of high energy physics, 05(5):195, and PUBDB-2021-02425, arXiv:2011.04678. HU-EP-20/33-RTG. DESY-20-191.
doi: 10.1007/JHEP05(2021)195.

V. V. Bazhanov, G. Kotoousov and S. L. Lukyanov.
Equilibrium density matrices for the 2D black hole sigma models from an integrable spin chain.
Journal of high energy physics, 03(3):169, and PUBDB-2021-01964, arXiv:2010.10603. DESY-20-165.
doi: 10.1007/JHEP03(2021)169.

V. V. Bazhanov et al.
Scaling limit of the Z_2 invariant inhomogeneous six-vertex model.
Nuclear physics / B, 965:115337, and PUBDB-2021-01965, arXiv:2010.10613. DESY-20-166.
doi: 10.1016/j.nuclphysb.2021.115337.

V. V. Bazhanov et al.
Some Algebraic Aspects of the Inhomogeneous Six-Vertex Model.
Symmetry, integrability and geometry: methods and applications, 17:29, and PUBDB-2021-01966, arXiv:2010.10615. DESY-20-167.
doi: 10.3842/SIGMA.2021.025.

P. Bechtle et al.
HiggsSignals-2: Probing new physics with precision Higgs measurements in the LHC 13 TeV era.
The European physical journal / C, 81(2):145 (1, and PUBDB-2021-02170, arXiv:2012.09197. BONN-TH-2020-09. DESY-20-228. IFT-UAM/CSIC-20-081. LU TP 20-53.
doi: 10.1140/epjc/s10052-021-08942-y.

V. N. Bennert et al.
A Local Baseline of the Black Hole Mass Scaling Relations for Active Galaxies. IV. Correlations Between M BH and Host Galaxy σ, Stellar Mass, and Luminosity.
The astrophysical journal, 921(1):36, and PUBDB-2022-00254, arXiv:2101.10355.
doi: 10.3847/1538-4357/ac151a.

S. Bertolini, L. Di Luzio and F. Nesti.
Axion-mediated forces, CP violation and left-right interactions.
Physical review letters, 126(8):081801, and PUBDB-2021-01960, arXiv:2006.12508. DESY-20-103.
doi: 10.1103/PhysRevLett.126.081801.

T. Biekoetter.
munuSSM: A python package for the μ-from-ν Supersymmetric Standard Model.
Computer physics communications, 264:107935, and

PUBDB-2021-01514, arXiv:2009.12887. DESY-20-162.
doi: 10.1016/j.cpc.2021.107935.

T. Biekoetter, M. Chakraborti and S. Heinemeyer.
The “96 GeV excess” at the LHC.
International journal of modern physics / A, 36(22):2142018, and PUBDB-2022-00247, arXiv:2003.05422. IFT-UAM/CSIC-20-041. DESY-20-047.
doi: 10.1142/S0217751X21420185.

T. Biekoetter and M. O. Olea Romacho.
Reconciling Higgs physics and pseudo-Nambu-Goldstone dark matter in the S2HDM using a genetic algorithm.
Journal of high energy physics, 10:215, and PUBDB-2022-00112, arXiv:2108.10864. DESY-21-125.
doi: 10.1007/JHEP10(2021)215.

T. Biekoetter et al.
Fate of electroweak symmetry in the early Universe: Non-restoration and trapped vacua in the N2HDM.
Journal of cosmology and astroparticle physics, 06:018, and PUBDB-2021-02617, arXiv:2103.12707. DESY-21-034. IFT-UAM/CSIC-21-018.
doi: 10.1088/1475-7516/2021/06/018.

G. Billis et al.
A toolbox for q_T and 0-jettiness subtractions at N^3LO.
The European physical journal / Plus, 136(2):214 (1, and PUBDB-2021-01958, arXiv:1909.00811. MIT-CTP/5140. DESY-19-145.
doi: 10.1140/epjp/s13360-021-01155-y.

G. Billis et al.
Higgs p_T Spectrum and Total Cross Section with Fiducial Cuts at Third Resummed and Fixed Order in QCD.
Physical review letters, 127(7):072001, and PUBDB-2021-04502, arXiv:2102.08039. DESY-21-022. MPP-2021-16. MIT-CTP 5266.
doi: 10.1103/PhysRevLett.127.072001.

F. Bishara et al.
Precision from the diphoton Zh channel at FCC-hh.
Journal of high energy physics, 04(4):154 (1, and PUBDB-2021-01973, arXiv:2011.13941. DESY-20-200. HU-EP-20/35. ZU-TH-43/20. PSI-PR-20-20.
doi: 10.1007/JHEP04(2021)154.

F. A. Bishara et al.
Generic One-Loop Matching Conditions for Rare Meson Decays.
Journal of high energy physics, 07(7):230, and PUBDB-2021-04795, arXiv:2104.10930. DESY-21-053.
doi: 10.1007/JHEP07(2021)230.

J. Blümlein and M. Saragnese.
The N^3LO scheme-invariant QCD evolution of the non-singlet structure functions $F_2^{NS}(x,Q^2)$ and $g_1^{NS}(x,Q^2)$.
Physics letters / B, 820:136589, and PUBDB-2021-03759, arXiv:2107.01293. DESY-21-096. SAGEX-21-13-E. DO-TH 21/21.
doi: 10.1016/j.physletb.2021.136589.

J. Blümlein et al.
The three-loop unpolarized and polarized non-singlet anomalous dimensions from off shell operator matrix elements.
Nuclear physics / B, 971:115542 (1, and PUBDB-2021-03956, arXiv:2107.06267. DESY-21-104. DO–TH 21/23. TTP 21–024. RISC Report Series 21–13. SAGEX–21–15.
doi: 10.1016/j.nuclphysb.2021.115542.

J. Blümlein, A. De Freitas and K. Schönwald.
The QED Initial State Corrections to the Forward-Backward Asymmetry of $e^+e^- \to \gamma^*/Z^{0*}$ to Higher Orders.
Physics letters / B, 816:1, and PUBDB-2021-02141, arXiv:2102.12237. DESY-21-013. DO–TH 21/04. TTP21–004. SAGEX–21–03.
doi: 10.1016/j.physletb.2021.136250.

J. Blümlein et al.
The 6th Post-Newtonian Potential Terms at $O(G_N^4)$.
Physics letters / B, 816:136260, and PUBDB-2021-01781, arXiv:2101.08630. DESY-20-199. DO-TH 20/06. SAGEX-20-08.
doi: 10.1016/j.physletb.2021.136260.

J. Blümlein et al.
The fifth-order post-Newtonian Hamiltonian dynamics of two-body systems from an effective field theory approach: Potential contributions.
Nuclear physics / B, 965:115352, and PUBDB-2021-01236, arXiv:2010.13672. DESY-20-062. DO-TH 20/04. SAGEX-20-10.
doi: 10.1016/j.nuclphysb.2021.115352.

D. Bodeker and W. Buchmuller.
Baryogenesis from the weak scale to the grand unification scale.
Reviews of modern physics, 93(3):035004 (1, and PUBDB-2021-04522, arXiv:2009.07294. DESY-20-141.
doi: 10.1103/RevModPhys.93.035004.

Q. R. C. Bonnefoy, E. Gendy and C. Grojean.
Positivity bounds on Minimal Flavor Violation.
Journal of high energy physics, 04(4):115 (1, and PUBDB-2021-01974, arXiv:2011.12855. DESY-20-201.
doi: 10.1007/JHEP04(2021)115.

Q. R. C. Bonnefoy et al.
Comments on gauge anomalies at dimension-six in the Standard Model Effective Field Theory.
Journal of high energy physics, 05(5):153, and PUBDB-2022-01011, arXiv:2012.07740. DESY-20-220. HU-EP-20/40.
doi: 10.1007/JHEP05(2021)153.

Q. R. C. Bonnefoy et al.
Flavoured Warped Axion.
Journal of high energy physics, 04(4):084, and PUBDB-2021-02427, arXiv:2012.09728. UMN-TH-4007/20. DESY-20-218. CPHT-RR094.122020.
doi: 10.1007/JHEP04(2021)084.

Q. R. C. Bonnefoy et al.
The anomalous case of axion EFTs and massive chiral gauge fields.
Journal of high energy physics, 07(7):189 (1, and PUBDB-2021-04069, arXiv:2011.10025. DESY-20-194. HU-EP-20/32.
doi: 10.1007/JHEP07(2021)189.

Q. R. C. Bonnefoy et al.
The swampland at large number of space-time dimensions.
Journal of high energy physics, 07(7):009 (1, and PUBDB-2021-03121, arXiv:2011.06610. DESY-20-185. LMU-ASC 40/20. MPP-2020-192.
doi: 10.1007/JHEP07(2021)009.

T. Bourton, A. Pini and E. Pomoni.
The Coulomb and Higgs branches of $\mathcal{N}=1$ theories of Class $\mathcal{S}_k$.
Journal of high energy physics, 02(2):137, and PUBDB-2021-04794, arXiv:2011.01587. DESY-19-222.
doi: 10.1007/JHEP02(2021)137.

J. Braathen and S. Kanemura.
Two-loop corrections to the Higgs trilinear coupling in models with extended scalar sectors.
Proceedings of Science / International School for Advanced Studies, 390:1, and PUBDB-2021-01978, arXiv:2012.05730. OU-HET-1083. DESY-20-217.
doi: PoS ICHEP2020 (2021) 051.

J. Braathen, S. Kanemura and M. Shimoda.
Two-loop analysis of classically scale-invariant models with extended Higgs sectors.
Journal of high energy physics, 03(3):297 (1, and PUBDB-2021-01972, arXiv:2011.07580. OU-HET-1077. DESY-20-192.
doi: 10.1007/JHEP03(2021)297.

J. Braathen et al.
Expectation management.
The European physical journal / C, 81(6):498 (1, and PUBDB-2021-03152, arXiv:2103.06773. DESY-21-030. TTK-21-07.
doi: 10.1140/epjc/s10052-021-09285-4.

T. Bringmann et al.
Dark Matter from Exponential Growth.
Physical review letters, 127(19):191802 (1, and PUBDB-2021-05447.
doi: 10.1103/PhysRevLett.127.191802.

T. Bringmann et al.
Precise dark matter relic abundance in decoupled sectors.
Physics letters / B, 817:136341, and PUBDB-2022-00219, arXiv:2007.03696. DESY-20-113.
doi: 10.1016/j.physletb.2021.136341.

W. Buchmuller.
Metastable strings and dumbbells in supersymmetric hybrid inflation.
Journal of high energy physics, 04(4):168, and PUBDB-2021-03148, arXiv:2102.08923. DESY-21-021. arXiv:2102.08923.
doi: 10.1007/JHEP04(2021)168.

W. Buchmuller, V. Domcke and K. R. Schmitz.
Stochastic gravitational-wave background from metastable cosmic strings.
Journal of cosmology and astroparticle physics, 12(12):006 (1, and PUBDB-2022-00072, arXiv:2107.04578. CERN-TH-2021-107. DESY-21-101.
doi: 10.1088/1475-7516/2021/12/006.

W. Buchmuller, E. Dudas and Y. Tatsuta.
Tachyon condensation in magnetic compactifications.
Journal of high energy physics, 03(3):070, and PUBDB-2021-01963, arXiv:2010.10891. CPHT-RR066.092020. DESY-20-163.
doi: 10.1007/JHEP03(2021)070.

M. G. A. Buffing, M. Diehl and T. Kasemets.
Erratum to: Transverse momentum in double parton scattering: factorisation, evolution and matching.
Journal of high energy physics, 07(7):046, and PUBDB-2022-00208, arXiv:1708.03528. NIKHEF-2016-028. DESY-17-014.
doi: 10.1007/JHEP07(2021)046.

I. Buric.
Harmonic Analysis in d-dimensional Superconformal Field Theory.
Symmetry, integrability and geometry: methods and applications, 17:38, and PUBDB-2021-01105, arXiv:2009.00393. DESY-20-139.
doi: 10.3842/SIGMA.2021.007.

I. Buric, V. Schomerus and E. Sobko.
Crossing symmetry for long multiplets in 4D $\mathcal{N}=1$ SCFTs.
Journal of high energy physics, 04(4):130 (1, and PUBDB-2021-01976, arXiv:2011.14116. DESY-20-205.
doi: 10.1007/JHEP04(2021)130.

I. Buric et al.
From Gaudin Integrable Models to d-dimensional Multipoint Conformal Blocks.
Physical review letters, 126(2):021602, and PUBDB-2021-00650, arXiv:2009.11882. DESY-20-157. ZMP-HH/20-25.
doi: 10.1103/PhysRevLett.126.021602.

I. Buric et al.
Gaudin models and multipoint conformal blocks: general theory.
Journal of high energy physics, 10(10):139, and PUBDB-2022-00042, arXiv:2105.00021. DESY-21-052. SAGEX21-08-E. ZMP-HH/21-8.
doi: 10.1007/JHEP10(2021)139.

I. Buric et al.
Gaudin models and multipoint conformal blocks. Part II. Comb channel vertices in 3D and 4D.
Journal of high energy physics, 11(11):182, and PUBDB-2022-00106, arXiv:2108.00023. SAGEX-21-14-E. ZMP-HH/21-15. DESY-21-105.
doi: 10.1007/JHEP11(2021)182.

I. Burić and V. Schomerus.
Defect Conformal Blocks from Appell Functions.
Journal of high energy physics, 05(5):007, and PUBDB-2021-02423, arXiv:2012.12489. DESY-20-206.
doi: 10.1007/JHEP05(2021)007.

K. U. Can et al.
Lattice QCD evaluation of the Compton amplitude employing the Feynman-Hellmann theorem.
Physical review / D, 102(11):114505, and PUBDB-2021-01451, arXiv:2007.01523. ADP-20-16/T1126. DESY-20-111. Liverpool LTH 1238.
doi: 10.1103/PhysRevD.102.114505.

A. Caputo et al.
Edges and Endpoints in 21-cm Observations from Resonant Photon Production.
Physical review letters, 127(1):011102 (1, and PUBDB-2021-02932, arXiv:2009.03899. DESY-20-143.
doi: 10.1103/PhysRevLett.127.011102.

F. Carta et al.
Gopakumar-Vafa hierarchies in winding inflation and uplifts.
Journal of high energy physics, 05(5):271, and PUBDB-2021-03131, arXiv:2101.07272. DESY-21-007. IFT-UAM/CSIC-21-3.
doi: 10.1007/JHEP05(2021)271.

V. Chestnov and G. Papathanasiou.
Hexagon bootstrap in the double scaling limit.
Journal of high energy physics, 09(9):007, and PUBDB-2021-04529, arXiv:2012.15855. DESY-20-221.
doi: 10.1007/JHEP09(2021)007.

D. Chicherin, J. M. Henn and G. Papathanasiou.
Cluster algebras for Feynman integrals.
Physical review letters, 126(9):091603, and PUBDB-2021-01515, arXiv:2012.12285. DESY-20-204. MPP-2020-216.
doi: 10.1103/PhysRevLett.126.091603.

G. Choi, R. Jinno and T. T. Yanagida.
Probing PeV scale SUSY breaking with satellite galaxies and primordial gravitational waves.
Physical review / D, 104(9):095018, and PUBDB-2022-00108, arXiv:2107.12804. DESY-21-112.
doi: 10.1103/PhysRevD.104.095018.

L. Cieri and G. Sborlini.
Exploring QED Effects to Diphoton Production at Hadron Colliders.
Symmetry, 13(6):994, and PUBDB-2021-02714, DESY-21-055.
doi: 10.3390/sym13060994.

M. Ciuchini et al.
Lessons from the $B^{0,+} \to K^{*0,+}\mu^+\mu^-$ angular analyses.
Physical review / D, 103(1):015030, and PUBDB-2021-01097, arXiv:2011.01212. DESY-20-190. HU-EP-20/30. TTP20-037. P3H-20-064. UCI-TR 2020-18.
doi: 10.1103/PhysRevD.103.015030.

M. Constantinou et al.
Parton distributions and lattice-QCD calculations: Toward 3D structure.
Progress in particle and nuclear physics, 121:103908, and PUBDB-2022-00363, arXiv:2006.08636. Nikhef 2020-018. MIT-CTP/5213. MSUHEP-20-012. IFJPAN-IV-2020-3. SMU-HEP-20-03. DESY-20-109.
doi: 10.1016/j.ppnp.2021.103908.

CSSM/QCDSF/UKQCD Collaboration.
State mixing and masses of the π^0, η and η' mesons from $n_f = 1+1+1$ lattice QCD+QED.
Physical review / D, 104(11):114514, and PUBDB-2022-01014, arXiv:2110.11533. ADP-21-16/T1163. DESY-21-166. LTH 1270.
doi: 10.1103/PhysRevD.104.114514.

G. D'Amico, N. Kaloper and A. Westphal.
Double Monodromy Inflation: A Gravity Waves Factory for CMB-S4, LiteBIRD and LISA.
Physical review / D, 104(8):L081302, and PUBDB-2021-04768, arXiv:2101.05861. DESY-21-004.
doi: 10.1103/PhysRevD.104.L081302.

F. D'Eramo and A. Lenoci.
Lower mass bounds on FIMP dark matter produced via freeze-in.
Journal of cosmology and astroparticle physics, 10(10):045, and PUBDB-2021-04527, arXiv:2012.01446. DESY-20-219.
doi: 10.1088/1475-7516/2021/10/045.

L. Darmé et al.
Selective enhancement of the QCD axion couplings.
Physical review / D, 103(1):015034, and PUBDB-2021-01110, arXiv:2010.15846. DESY-20-177. DESY-20-177.
doi: 10.1103/PhysRevD.103.015034.

P. F. Depta, M. Hufnagel and K. Schmidt-Hoberg.
ACROPOLIS: A generiC fRamework fOr Photodisintegration Of LIght elementS.
Journal of cosmology and astroparticle physics, 03(03):061, and PUBDB-2021-01962, arXiv:2011.06518. DESY-20-161. ULB-TH/20-16.
doi: 10.1088/1475-7516/2021/03/061.

P. F. Depta, M. Hufnagel and K. Schmidt-Hoberg.
Updated BBN constraints on electromagnetic decays of MeV-scale particles.
Journal of cosmology and astroparticle physics, 04(04):011, and PUBDB-2022-00387, arXiv:2011.06519. DESY-20-160. ULB-TH/20-15.
doi: 10.1088/1475-7516/2021/04/011.

L. Di Luzio, R. Gröber and P. Paradisi.
Hunting for CP-violating axionlike particle interactions.
Physical review / D, 104(9):095027, and PUBDB-2022-00490, arXiv:2010.13760. DESY-20-183.
doi: 10.1103/PhysRevD.104.095027.

L. Di Luzio, G. Martinelli and G. Piazza.
Breakdown of chiral perturbation theory for the axion hot dark matter bound.
Physical review letters, 126(24):241801, and PUBDB-2021-03146, arXiv:2101.10330. DESY-21-012.
doi: 10.1103/PhysRevLett.126.241801.

L. Di Luzio et al.
An even lighter QCD axion.
Journal of high energy physics, 2021(5):184 (1, and PUBDB-2021-02793, DESY-21-010. IFT-UAM/CSIC-20-143. FTUAM-20-21. arXiv:2102.00012.
doi: 10.1007/JHEP05(2021)184.

L. Di Luzio et al.
Dark matter from an even lighter QCD axion: trapped misalignment.
Journal of cosmology and astroparticle physics, 2021(10):001, and PUBDB-2021-04106, DESY-21-011. IFT-UAM/CSIC-20-144. FTUAM-20-21. arXiv:2102.01082.
doi: 10.1088/1475-7516/2021/10/001.

M. Diehl, J. R. Gaunt and P. J. Ploessl.
Two-loop splitting in double parton distributions: the colour non-singlet case.
Journal of high energy physics, 08(8):040, and PUBDB-2021-05190, arXiv:2105.08425. DESY-21-015. MAN/HEP/2021/002. arXiv:2105.08425.
doi: 10.1007/JHEP08(2021)040.

M. Diehl et al.
Double parton distributions out of bounds in colour space.
The European physical journal / C, 81(11):1033, and PUBDB-2022-00116, arXiv:2109.14304. DESY-21-148. UUITP-46/21.
doi: 10.1140/epjc/s10052-021-09822-1.

M. J. Dolan et al.
Erratum to: Revised constraints and Belle II sensitivity for visible and invisible axion-like particles.
Journal of high energy physics, 2021(3):190, and PUBDB-2022-00326, arXiv:1709.00009. DESY-17-127.
doi: 10.1007/JHEP03(2021)190.

V. Domcke, Y. Ema and K. Mukaida.
Axion assisted Schwinger effect.
Journal of high energy physics, 05(5):001, and PUBDB-2021-03129, arXiv:2101.05192. DESY-21-006. CERN-TH-2021-010.
doi: 10.1007/JHEP05(2021)001.

V. Domcke and C. Garcia-Cely.
Potential of radio telescopes as high-frequency gravitational wave detectors.
Physical review letters, 126(2):021104, and PUBDB-2021-01100, arXiv:2006.01161. DESY-20-097. CERN-TH-2020-082.
doi: 10.1103/PhysRevLett.126.021104.

V. Domcke et al.
MeV-scale Seesaw and Leptogenesis.
Journal of high energy physics, 01(1):200, and PUBDB-2021-01107, arXiv:2009.11678. CERN-TH-2020-158. DESY-20-159.
doi: 10.1007/JHEP01(2021)200.

V. Domcke et al.
Wash-In Leptogenesis.
Physical review letters, 126(20):201802, and PUBDB-2021-02426, arXiv:2011.09347. CERN-TH-2020-196. RESCEU-22/20. DESY-20-202. TU-1112.
doi: 10.1103/PhysRevLett.126.201802.

G. C. Dorsch, S. J. Huber and T. Konstandin.
On the wall velocity dependence of electroweak baryogenesis.
Journal of cosmology and astroparticle physics, 08(08):020, and PUBDB-2021-04790, arXiv:2106.06547. DESY-21-089.
doi: 10.1088/1475-7516/2021/08/020.

M. A. Ebert et al.
Drell-Yan q_T resummation of fiducial power corrections at N^3LL.
Journal of high energy physics, 04(4):102, and PUBDB-2022-00484, arXiv:2006.11382. DESY-20-016. MIT-CTP 5205.
doi: 10.1007/JHEP04(2021)102.

Y. Ema, K. Mukaida and J. M. v. d. Vis.
Renormalization group equations of Higgs-R^2 inflation.
Journal of high energy physics, 02:109, and PUBDB-2021-01104, arXiv:2008.01096. DESY-20-130.
doi: 10.1007/JHEP02(2021)109.

Y. Ema, F. Sala and R. Sato.
Dark matter models for the 511 keV galactic line predict keV electron recoils on Earth.
The European physical journal / C, 81(2):129 (1, and PUBDB-2021-02169, arXiv:2007.09105. DESY-20-120.
doi: 10.1140/epjc/s10052-021-08899-y.

Y. Ema, F. Sala and R. Sato.
Neutrino experiments probe hadrophilic light dark matter.
SciPost physics, 10(3):072, and PUBDB-2022-00520, arXiv:2011.01939.
doi: 10.21468/SciPostPhys.10.3.072.

Y. Ema et al.
Preheating from target space curvature and unitarity violation: Analysis in field space.
Physical review / D, 103(10):103536, and PUBDB-2021-03150, arXiv:2102.12501. DESY-21-027.
doi: 10.1103/PhysRevD.103.103536.

Extended Twisted Mass Collaboration.
Nucleon axial and pseudoscalar form factors from lattice QCD at the physical point.
Physical review / D, 103(3):034509, and PUBDB-2021-01214, arXiv:2011.13342.
doi: 10.1103/PhysRevD.103.034509.

Extended Twisted Mass Collaboration.
Quark masses using twisted-mass fermion gauge ensembles.
Physical review / D, 104(7):074515, and PUBDB-2021-04383, arXiv:2104.13408.
doi: 10.1103/PhysRevD.104.074515.

A. Falkowski, G. Isabella and C. Sampaio Machado.
On-shell effective theory for higher-spin dark matter.
SciPost physics, 10(5):101, and PUBDB-2022-00344, arXiv:2011.05339. DESY-20-198.
doi: 10.21468/SciPostPhys.10.5.101.

R. R. Ferguson et al.
Measurement-Based Variational Quantum Eigensolver.
Physical review letters, 126(22):220501, and PUBDB-2021-02622, arXiv:2010.13940. DESY-20-197.
doi: 10.1103/PhysRevLett.126.220501.

M. S. Fischer et al.
Unequal-mass mergers of dark matter haloes with rare and frequent self-interactions.
Monthly notices of the Royal Astronomical Society, 0:stab3544 (1, and PUBDB-2021-05446, arXiv:2109.10035. DESY-21-116.
doi: 10.1093/mnras/stab3544.

P. Foldenauer, F. Kling and P. Reimitz.
Potential of CMS as a high-energy neutrino scattering experiment.
Physical review / D, 104(11):113005, and PUBDB-2022-00941, arXiv:2108.05370. IPPP/21/10. DESY-21-120.
doi: 10.1103/PhysRevD.104.113005.

N. Fonseca et al.
Erratum to: Relaxion fluctuations (self-stopping relaxion) and overview of relaxion stopping mechanisms.
Journal of high energy physics, 2021(1):012, and PUBDB-2022-00290, arXiv:1911.08473. DESY-19-203.
doi: 10.1007/JHEP01(2021)012.

L. Funcke et al.
Dimensional Expressivity Analysis of Parametric Quantum Circuits.
Quantum, 5:422, and PUBDB-2021-02288, arXiv:2011.03532. HU-EP-20/31.
doi: 10.22331/q-2021-03-29-422.

GAMBIT Collaboration.
Thermal WIMPs and the scale of new physics: global fits of Dirac dark matter effective field theories.
The European physical journal / C, 81(11):992, and PUBDB-2022-00544, arXiv:2106.02056. ADP-21-9/T1156. CERN-TH-2021-084. CP3-21-15. P3H-21-038. TTK-21-19. gambit-physics-21.
doi: 10.1140/epjc/s10052-021-09712-6.

M. Garny et al.
Neutrino mass bounds from confronting an effective model with BOSS Lyman-α data.
Journal of cosmology and astroparticle physics, 03(03):049, and PUBDB-2021-01968, arXiv:2011.03050. DESY-20-174. TUM-HEP-1294/20. TTK-20-36.
doi: 10.1088/1475-7516/2021/03/049.

A. P. Gautham et al.
Reconciling hints on axion-like-particles from high-energy gamma rays with stellar bounds.
Journal of cosmology and astroparticle physics, 11(11):036 (1, and PUBDB-2021-04520, arXiv:2008.08100. DESY-20-121.
doi: 10.1088/1475-7516/2021/11/036.

K. Ghosh, A. Kaviraj and M. F. Paulos.
Charging up the functional bootstrap.
Journal of high energy physics, 10(10):116, and PUBDB-2022-00286, arXiv:2107.00041.
doi: 10.1007/JHEP10(2021)116.

F. Giese, T. Konstandin and J. M. v. d. Vis.
Finding sound shells in LISA mock data using likelihood samplin.
Journal of cosmology and astroparticle physics, 11(11):002, and PUBDB-2021-04772, arXiv:2107.06275. DESY-21-109.
doi: 10.1088/1475-7516/2021/11/002.

F. Giese et al.
Model-independent energy budget for LISA.
Journal of cosmology and astroparticle physics, 01:072, and PUBDB-2021-01109, arXiv:2010.09744. DESY-20-173. CERN-TH-2020-170.
doi: 10.1088/1475-7516/2021/01/072.

A. Gimenez-Grau and P. Liendo.
Bootstrapping Coulomb and Higgs branch operators.
Journal of high energy physics, 01(1):175, and PUBDB-2021-01102, arXiv:2006.01847. DESY-20-099.
doi: 10.1007/JHEP01(2021)175.

A. Gimenez-Grau, P. Liendo and P. J. v. Vliet.
Superconformal boundaries in $4-\epsilon$ dimensions.
Journal of high energy physics, 04(4):167 (1, and PUBDB-2021-01977, arXiv:2012.00018. DESY-20-215.
doi: 10.1007/JHEP04(2021)167.

C. Grojean, A. Paul and Z. Qian.
Resurrecting $b\bar{b}h$ with kinematic shapes.
Journal of high energy physics, 04(4):139, and PUBDB-2021-01969, arXiv:2011.13945. DESY-20-175. HU-EP-20/28.
doi: 10.1007/JHEP04(2021)139.

J. F. Haase et al.
A resource efficient approach for quantum and classical simulations of gauge theories in particle physics.
Quantum, 5:393, and PUBDB-2021-01240, arXiv:2006.14160. DESY-20-146.
doi: 10.22331/q-2021-02-04-393.

T. Han et al.
Precision test of the muon-Higgs coupling at a high-energy muon collider.
Journal of high energy physics, 12(12):162, and PUBDB-2022-00328, arXiv:2108.05362. DESY-21-068. PITT-PACC-2110.
doi: 10.1007/JHEP12(2021)162.

T. Hartung et al.
Lattice meets lattice: Application of lattice cubature to models in lattice gauge theory.
Journal of computational physics, 443:110527, and PUBDB-2022-00513, arXiv:2011.05451. DESY-20-209.
doi: 10.1016/j.jcp.2021.110527.

M. He et al.
Occurrence of tachyonic preheating in the mixed Higgs-R^2 model.
Journal of cosmology and astroparticle physics, 01:066, and PUBDB-2021-01103, arXiv:2007.10369. DESY-20-126. RESCEU-13/20.
doi: 10.1088/1475-7516/2021/01/066.

Y.-C. He, J. Rong and N. Su.
Non-Wilson-Fisher kinks of $O(N)$ numerical bootstrap: from the deconfined phase transition to a putative new family of CFTs.
SciPost physics, 10(5):115 (1, and PUBDB-2021-03126, arXiv:2005.04250. https://arxiv.org/abs/2005.04250.
doi: 10.21468/SciPostPhys.10.5.115.

N. Henke and G. Papathanasiou.
Singularities of eight- and nine-particle amplitudes from cluster algebras and tropical geometry.
Journal of high energy physics, 10(10):007, and PUBDB-2022-00581, arXiv:2106.01392.
doi: 10.1007/JHEP10(2021)007.

N. A. Husung, P. Marquard and R. Sommer.
Logarithmic corrections to a^2 scaling in lattice QCD with Wilson and Ginsparg-Wilson quarks.
The 38th International Symposium on Lattice Field Theory, LATTICE2021 26th-30th July, 2021 Zoom/Gather@Massachusetts Institute of Technology, Online (United States), 26 Jul 2021 - 30 Jul 2021.

Proceedings of Science / International School for Advanced Studies, vol. (LATTICE2021):7, and PUBDB-2021-04338, DESY-21-178. arXiv:2111.04679.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-04338.

IAXO Collaboration.
Conceptual design of BabyIAXO, the intermediate stage towards the International Axion Observatory.
Journal of high energy physics, 05(5):137, and PUBDB-2022-00309, arXiv:2010.12076.
doi: 10.1007/JHEP05(2021)137.

K. Inomata et al.
NANOGrav Results and LIGO-Virgo Primordial Black Holes in Axionlike Curvaton Models.
Physical review letters, 126(13):131301, and PUBDB-2021-01971, arXiv:2011.01270. CERN-TH-2020-182. DESY-20-188.
doi: 10.1103/PhysRevLett.126.131301.

T. Ishikawa, K. Nakayama and K. Suzuki.
Kondo effect with Wilson fermions.
Physical review / D, 104(9):094515, and PUBDB-2022-00054, arXiv:2107.07270. KEK-TH-2338. DESY-21-110.
doi: 10.1103/PhysRevD.104.094515.

F. Jegerlehner.
The Standard Model of particle physics as a conspiracy theory and the possible role of the Higgs boson in the evolution of the early universe.
Acta physica Polonica / B, 52(6-7):575, and PUBDB-2021-03276, arXiv:2106.00862. DESY-21-073. HU-EP-21/12.
doi: 10.5506/APhysPolB.52.575.

R. Jinno, T. Konstandin and H. Rubira.
A hybrid simulation of gravitational wave production in first-order phase transitions.
Journal of cosmology and astroparticle physics, 04(04):014, and PUBDB-2021-01967, arXiv:2010.00971. DESY-20-170.
doi: 10.1088/1475-7516/2021/04/014.

R. Jinno and R. Sato.
Negative mode problem of false vacuum decay revisited.
Physical review / D, 104(9):096009 (1, and PUBDB-2021-05448, arXiv:2010.04462. DESY-20-171.
doi: 10.1103/PhysRevD.104.096009.

R. Jinno et al.
Effect of density fluctuations on gravitational wave production in first-order phase transitions.
Journal of cosmology and astroparticle physics, 2021(12):019, and PUBDB-2021-05437, arXiv:2108.11947. DESY-21-131.
doi: 10.1088/1475-7516/2021/12/019.

A. Kan et al.
Investigating a 3+1D Topological θ-Term in the Hamiltonian Formulation of Lattice Gauge Theories for Quantum and Classical Simulations.
Physical review / D, 104(3):034504, and PUBDB-2021-02356, arXiv:2105.06019.
doi: 10.1103/PhysRevD.104.034504.

H. Kim.
A constraint on light primordial black holes from the interstellar medium temperature.
Monthly notices of the Royal Astronomical Society, 504(4):5475, and PUBDB-2022-00535, arXiv:2007.07739.
doi: 10.1093/mnras/stab1222.

H. Kim and A. Paul.
Automated contact tracing: a game of big numbers in the time of COVID-19.
Interface, 18:20200954, and PUBDB-2022-00517.
doi: 10.1098/rsif.2020.0954.

T. Kimura and F. Nieri.
Intersecting Defects and Supergroup Gauge Theory.
Journal of physics / A, 54(43):435401, and PUBDB-2022-00389, arXiv:2105.02776. DESY-21-060.
doi: 10.1088/1751-8121/ac2716.

S. Knirck et al.
Simulating MADMAX in 3D: requirements for dielectric axion haloscopes.
Journal of cosmology and astroparticle physics, 2021(10):034 (1, and PUBDB-2021-04105, arXiv:2104.06553. MPP-2021-61. DESY-21-051.
doi: 10.1088/1475-7516/2021/10/034.

G. Kotoousov and S. L. Lukyanov.
ODE/IQFT correspondence for the generalized affine $\mathfrak{sl}(2)$ Gaudin model.
Journal of high energy physics, 09(9):201 (1, and PUBDB-2022-00069, arXiv:2106.01238. DESY-21-081.
doi: 10.1007/JHEP09(2021)201.

E. Lauria et al.
Line and surface defects for the free scalar field.
Journal of high energy physics, 01(1):060, and PUBDB-2021-01959, arXiv:2005.02413. DESY-20-082.
doi: 10.1007/JHEP01(2021)060.

P. Liendo and J. Rong.
Seeking SUSY fixed points in the $4-\epsilon$ expansion.
Journal of high energy physics, 12:033, and PUBDB-2022-00111, arXiv:2107.14515. DESY-21-114.
doi: 10.1007/JHEP12(2021)033.

Mass, Extended Twisted.
Quark and Gluon Momentum Fractions in the Pion from $N_f = 2+1+1$ Lattice QCD.
Physical review letters, 127(25):252001, and PUBDB-2021-05530, arXiv:2109.10692.
doi: 10.1103/PhysRevLett.127.252001.

M. Musso and R. K. Sheth.
Excursion set peaks in energy as a model for haloes.
Monthly notices of the Royal Astronomical Society, 508(3):3634, and PUBDB-2022-00337, arXiv:1907.09147.
doi: 10.1093/mnras/stab2640.

A. Nada and A. Ramos.
An analysis of systematic effects in finite size scaling studies using the gradient flow.
The European physical journal / C, 81(1):1, and PUBDB-2021-00157, arXiv:2007.12862. DESY-20-127. IFIC/20-38.
doi: 10.1140/epjc/s10052-020-08759-1.

Z. Nagy and D. E. Soper.
Summations of large logarithms by parton showers.
Physical review / D, 104(5):054049, and PUBDB-2021-04525, arXiv:2011.04773. DESY-20-181.
doi: 10.1103/PhysRevD.104.054049.

V. Niarchos et al.
(Mis-)Matching Type-B Anomalies on the Higgs Branch.
Journal of high energy physics, 01(1):106, and PUBDB-2021-01106, arXiv:2009.08375. CCTP-2020-10. DCPT-20/13. QMUL-PH-20-26. DESY-20-145. ITCP-IPP-2020/10.
doi: 10.1007/JHEP01(2021)106.

K. A. Nicoli et al.
Estimation of Thermodynamic Observables in Lattice Field Theories with Deep Generative Models.
Physical review letters, 126(3):032001 (1, and PUBDB-2021-00769, arXiv:2007.07115. DESY-20-148.
doi: 10.1103/PhysRevLett.126.032001.

NPLQCD Collaboration and QCDSF Collaboration.
Charged multihadron systems in lattice QCD+QED.
Physical review / D, 103(5):054504, and PUBDB-2021-01907, arXiv:2003.12130. DESY-20-028. FERMILAB-PUB-20-123-T. ICCUB-20-007. MIT-CTP/5183. NT@UW-20-03.
doi: 10.1103/PhysRevD.103.054504.

D. Pagani et al.
Automated EW corrections with isolated photons: $t\bar{t}\gamma$, $t\bar{t}\gamma\gamma$ and $t\gamma j$ as case studies.
Journal of high energy physics, 09(9):155 (1, and PUBDB-2022-00071, arXiv:2106.02059. DESY-21-083. LU-TP 21-19. TIF-UNIMI-2021-7.
doi: 10.1007/JHEP09(2021)155.

A. Pathak et al.
EFT for Soft Drop Double Differential Cross Section.
Journal of high energy physics, 04(4):032, and PUBDB-2021-02428, arXiv:2012.15568. MIT-CTP 5235. UWThPh 2020-31. Nikhef 2020-031. MAN/HEP/2020/011. DESY-20-239.
doi: 10.1007/JHEP04(2021)032.

A. Paul et al.
Emergence of universality in the transmission dynamics of COVID-19.
Scientific reports, 11(1):18891, and PUBDB-2022-00319.
doi: 10.1038/s41598-021-98302-3.

E. Pomoni, R. Rabe and K. Zoubos.
Dynamical spin chains in 4D $\mathcal{N} = 2$ SCFTs.
Journal of high energy physics, 08(8):127 (1, and PUBDB-2022-00070, arXiv:2106.08449. DESY-21-082.
doi: 10.1007/JHEP08(2021)127.

S. Ramirez-Uribe et al.
Four-loop scattering amplitudes journey into the forest.
The European Physical Society Conference on High-Energy Physics, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):732, and PUBDB-2021-03962, DESY-21-154. arXiv:2110.10605. IFIC/21-34. MPP-2021-169.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-03962.

D. Rentería-Estrada, R. Hernández-Pinto and G. F. R. Sborlini.
Elucidating the internal structure of hadrons through direct photon production.
The European Physical Society Conference on High-Energy Physics, Hamburg (Germany), 26 Jul 2021 - 30 Jul 2021.
Proceedings of Science / International School for Advanced Studies, vol. (EPS-HEP2021):4, and PUBDB-2021-03977, DESY-21-156. arXiv:2110.06103. DESY-21-156.
SISSA, Trieste.
doi: 10.3204/PUBDB-2021-03977.

D. F. Rentería-Estrada, R. J. Hernández-Pinto and G. F. R. Sborlini.
Analysis of the Internal Structure of Hadrons Using Direct Photon Production.
Symmetry, 13(6):942 (1, and PUBDB-2021-03961, arXiv:2104.14663. DESY-21-057.
doi: 10.3390/sym13060942.

A. Ringwald, K. Saikawa and C. Tamarit.
Primordial gravitational waves in a minimal model of particle physics and cosmology.
Journal of cosmology and astroparticle physics, 2021(02):046, and PUBDB-2021-01098, arXiv:2009.02050. DESY-20-135. KANAZAWA-20-06. TUM-HEP-1279-20.
doi: 10.1088/1475-7516/2021/02/046.

A. Ringwald, J. Schütte-Engel and C. Tamarit.
Gravitational waves as a big bang thermometer.
Journal of cosmology and astroparticle physics, 2021(03):054, and PUBDB-2021-01467, DESY-20-187. TUM-HEP-1293-20. arXiv:2011.04731.
doi: 10.1088/1475-7516/2021/03/054.

J. Rong and N. Su.
Bootstrapping the $\mathcal{N} = 1$ Wess-Zumino models in three dimensions.
Journal of high energy physics, 06(6):153, and PUBDB-2022-00411, arXiv:1910.08578.
doi: 10.1007/JHEP06(2021)153.

J. Rong and N. Su.
Bootstrapping the minimal $\mathcal{N} = 1$ superconformal field theory in three dimensions.
Journal of high energy physics, 06(6):154, and PUBDB-2022-00408, arXiv:1807.04434.
doi: 10.1007/JHEP06(2021)154.

H. Rubira and R. Voivodic.
The Effective Field Theory and Perturbative Analysis for Log-Density Fields.
Journal of cosmology and astroparticle physics, 03(03):070 (1, and PUBDB-2021-01975, arXiv:2011.12280. DESY-20-203.
doi: 10.1088/1475-7516/2021/03/070.

M. Sakamoto, M. Takeuchi and Y. Tatsuta.
Index theorem on $T^2/\mathbb{Z}_N$ orbifolds.
Physical review / D, 103(2):025009, and PUBDB-2021-00670, arXiv:2010.14214. KOBE-TH-20-06. DESY-20-178.
doi: 10.1103/PhysRevD.103.025009.

R. Sato.
SimpleBounce : a simple package for the false vacuum decay.
Computer physics communications, 258:107566, and PUBDB-2020-03811, arXiv:1908.10868. DESY-19-148.
doi: 10.1016/j.cpc.2020.107566.

G. F. R. Sborlini.
Geometrical approach to causality in multiloop amplitudes.
Physical review / D, 104(3):036014, and PUBDB-2021-03783, arXiv:2102.05062. DESY-21-017.
doi: 10.1103/PhysRevD.104.036014.

M. Schneider et al.
Simulating both parity sectors of the Hubbard Model with Tensor Networks.
Physical review / B, 104(15):155118, and PUBDB-2021-02998, arXiv:2106.13583.
doi: 10.1103/PhysRevB.104.155118.

SIMBA Collaboration.
Precision Global Determination of the $B \to X_s \gamma$ Decay Rate.
Physical review letters, 127(10):102001 (1, and PUBDB-2021-04284, arXiv:2007.04320. DESY-20-115. MIT-CTP 5220.
doi: 10.1103/PhysRevLett.127.102001.

P. Slavich et al.
Higgs-mass predictions in the MSSM and beyond.
The European physical journal / C, 81(5):450, and PUBDB-2022-00287, arXiv:2012.15629. DESY-20-229. IFT-UAM/CSIC-20-184. FR-PHENO-2020-021. KA-TP-23-2020. MPP-2020-235. P3H-20-086. TTK-20-53. FERMILAB-PUB-21-575-T.
doi: 10.1140/epjc/s10052-021-09198-2.

A. Sokolov and A. Ringwald.
Photophilic hadronic axion from heavy magnetic monopoles.
Journal of high energy physics, 2021(6):123 (1, and PUBDB-2021-02976, arXiv:2104.02574. DESY-21-046.
doi: 10.1007/JHEP06(2021)123.

W. J. Torres Bobadilla et al.
May the four be with you: Novel IR-subtraction methods to tackle NNLO calculations.
The European physical journal / C, 81(3):250, and PUBDB-2021-01774, arXiv:2012.02567. IFIC/20-54. MPP-2020-218. TTP20-043. P3H-20-079.
doi: 10.1140/epjc/s10052-021-08996-y.

Ph.D. Thesis

I. Buric.
Harmonic Analysis in Conformal and Superconformal Field Theory.
University of Hamburg, 2021.

P. F. Depta.
Dark Sector Cosmologies: Evolution and Constraints.
Universtät Hamburg, Hamburg, 2021.

F. Giese.
Corrections to the energy budget of early universe phase transitions.
Universität Hamburg, Hamburg, 2021.

A. Rossia.
A Glance into the Future of Particle Physics with Effective Field Theories.
Humboldt-Universität zu Berlin, 2021.

V. Rothe.
Automation of NLO QCD Corrections and the Application to N-Jet Processes at Lepton Colliders.
Universität Hamburg, Hamburg, 2021.

H. Rubira.
Across scales in our Universe: Gravitational Waves and the Large-Scale Structure.
Universität Hamburg, Hamburg, 2021.

ZEUS

Published

Z. Tu.
HERA data on azimuthal decorrelation and charged particle multiplicity spectra probing QCD dynamics and quantum entanglement effects.
1828482. 40th International Conference on High Energy Physics, Prague (virtual meeting), 28 Jul 2020 - 6 Aug 2020. *Proceedings of Science / International School for Advanced Studies*, vol. 390:1, and PUBDB-2021-02154, arXiv:2011.02875.
SISSA, Trieste.
doi: 10.22323/1.390.0513.

ZEUS Collaboration.
Azimuthal correlations in photoproduction and deep inelastic ep scattering at HERA.
Journal of high energy physics, 12(12):102, and PUBDB-2022-00142, arXiv:2106.12377. DESY-21-099.
doi: 10.1007/JHEP12(2021)102.

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